THE NEW THEORY OF EARTHQUAKES AND MOUNTAIN FORMATION, AS ILLUSTRATED BY PROCESSES NOW AT WORK IN THE DEPTHS OF THE SEA.

(With Maps I.–III.)

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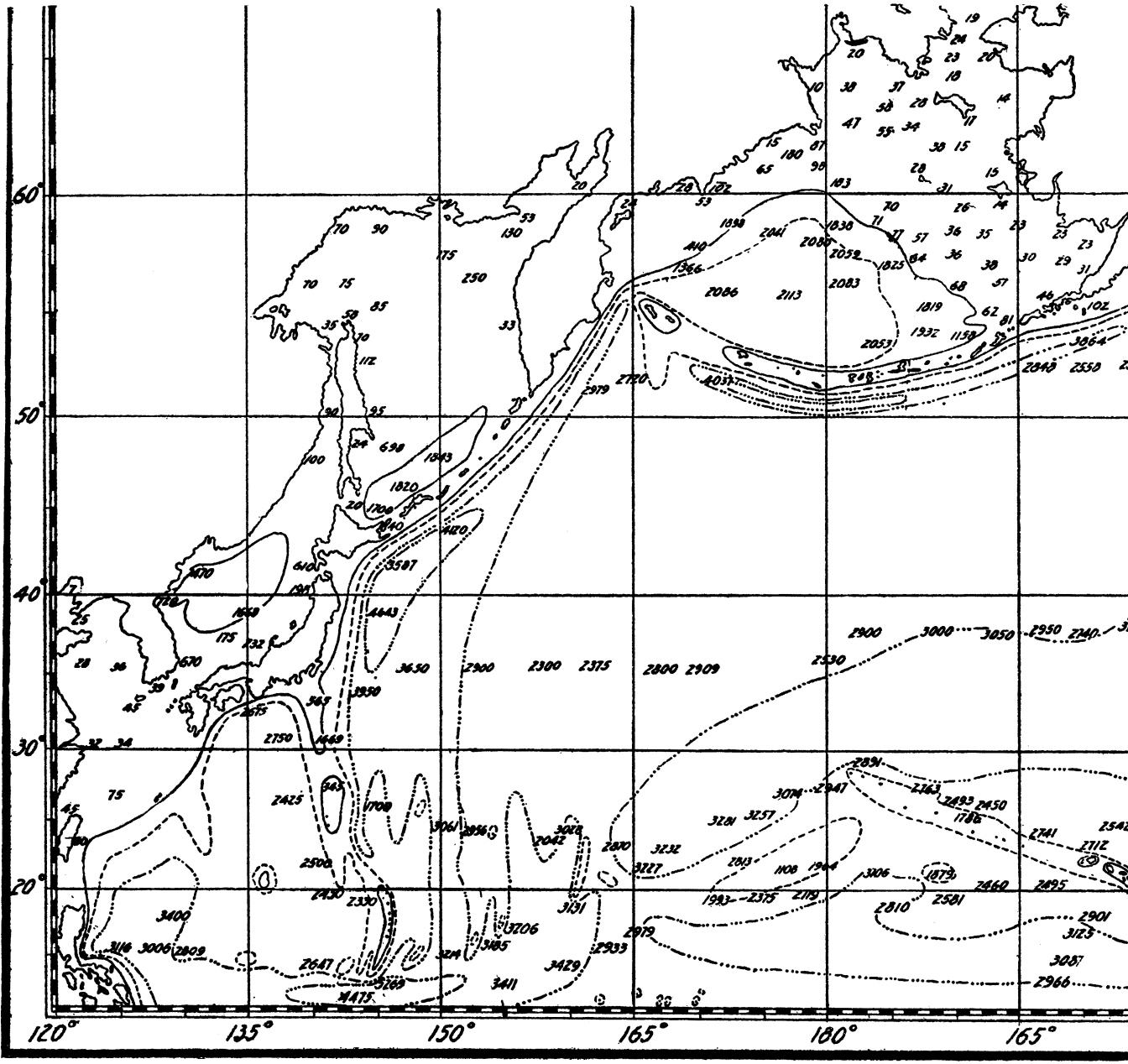
I. On Earthquake Processes Observed in the Depths of the Sea.

§ 1. *General Considerations.*—In two previous papers dealing respectively with the "Cause of Earthquakes" and the "Temperature of the Earth," a new theory has been developed which unites and harmonizes the most varied phenomena connected with the physics of the earth. These papers present the theory in a way which will no doubt seem convincing to the careful reader who has adequate experience in the physical sciences. But even the lay reader is entitled to all the light which may be shed on this difficult subject, and as the departure from previous theories is somewhat radical, it has seemed advisable to record some additional considerations which may be of interest also to the professional student of science.

This course seems the more appropriate in view of the established habits of thought of contemporary investigators, some of whom will naturally welcome any step which will simplify our understanding of physical phenomena. As the subject is extensive and complex and presented under various aspects in the different sciences, a connected view of the laws operating in the development of the earth's crust is by no means easy; for, if it were, the underlying cause no doubt would have been discovered long ago, and great improvements already would have been made in many of the physical sciences which deal with the terrestrial globe.

Accordingly if we are able to give concrete and convincing illustrations of the processes now at work in the depths of the sea, they will prove the new theory beyond doubt for certain cases; and then Newton's rule of continuity can be invoked to show that a cause conclusively established in certain cases must be held to be general for all cases whatsoever, where the phenomena are similar. To prove the general physical cause of earthquakes, therefore, we need certain illustrations which admit of but one interpretation, and where there can be no possible doubt about the true nature of the process. If this can be established for a few typical cases we may feel sure that all world-shaking earthquakes and mountain-forming processes depend upon the same physical cause; and that the smaller earthquakes, which are very numerous, depend upon the larger ones and upon the gradual settlement of the crust where for any reason it has become unstable. To unite the small with the large earthquakes, in the hope of finding from the whole body of phenomena, when combined indiscriminately, their general cause, would be to labor in vain; for in the case of the large world-shaking earthquakes there is movement of molten rock beneath the earth's crust, while in the case of small earthquakes the tremors are due to a variety of causes, but more especially to any kind of instability which may give rise to a small movement of the ground. As the earth's crust is thick and the true nature of the underlying movement hidden from our view by the depth at which it occurs, the process involved can not be recognized without excluding from consideration the small earthquakes, and dealing exclusively with those great world-shaking disturbances, in which the effects are so large that the nature of the hidden process can be discovered. The disturbances which show the underlying process most clearly are beneath the oceans, or along the coast of deep seas, where there is expulsion of lava from beneath the sea under the land. We shall now consider some particular cases in which the meaning is unmistakable, and which have only been alluded to in the former papers.

§ 2. *The great earthquakes now occurring in the sea near the Aleutian Islands are developing a high submarine mountain range, of which only a few peaks rise above the water.*—It is generally



COAST SURVEY MAP OF THE NORTH PACIFIC OCEAN, showing the deep trenches in the sea bottom dug out by Earthquakes in uplifting the Aleuti
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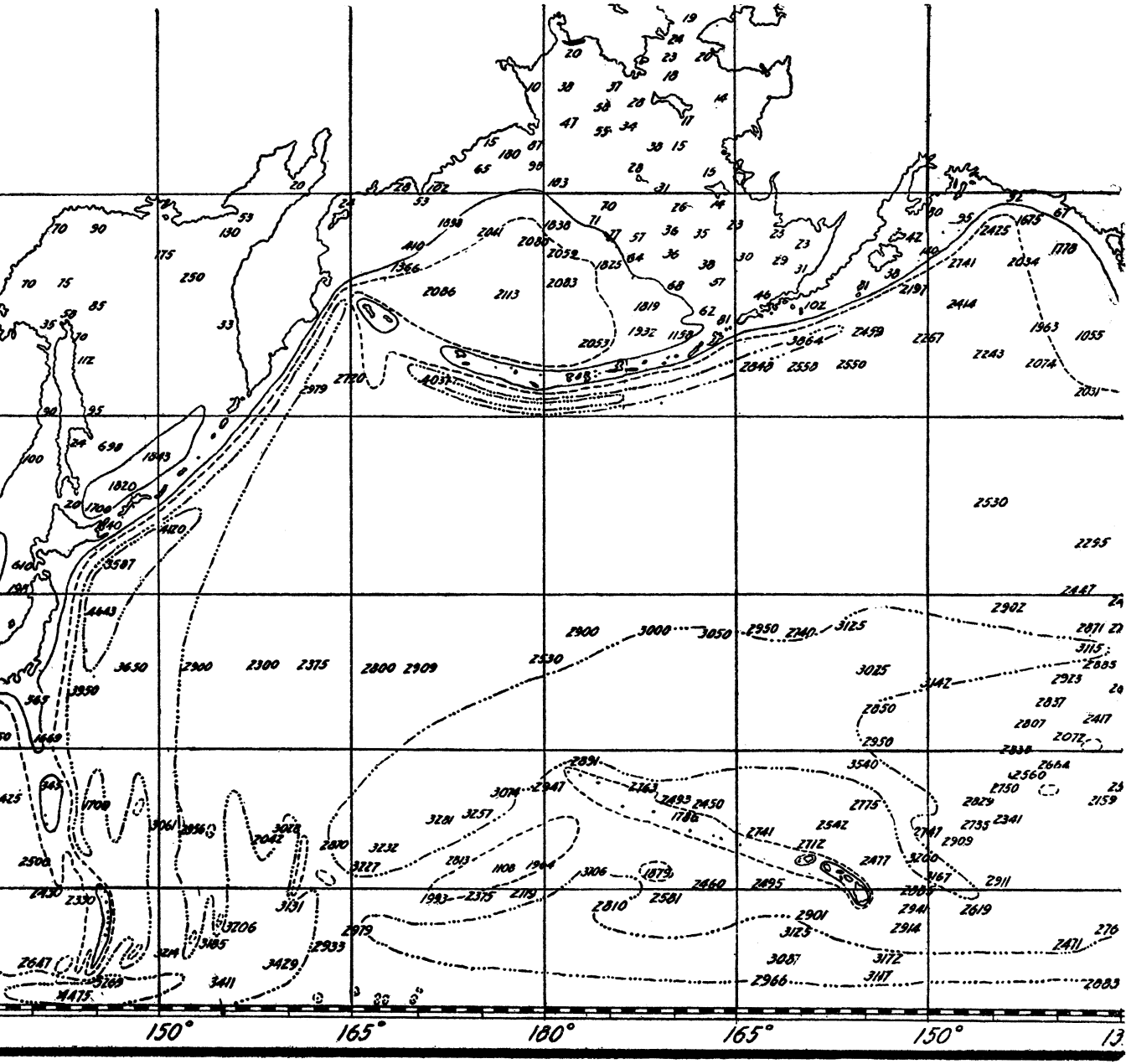

RTH PACIFIC OCEAN, showing the deep trenches in the sea bottom dug out by Earthquakes in uplifting the Aleutian, Kurile and Japanese Islands. In
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recognized by investigators that the most active region of seismic disturbances is along the Aleutian, Kurile, and Japanese Islands, and in the East Indies. Major Dutton not only speaks of the tremendous power of the mighty earthquakes in this region, but also calls attention to the prevalence of seismic sea waves following the earthquakes. "The profound depths of the ocean just off the eastern part of the Aleutian chain is one of the great breeding-grounds of world-shakers. A rather small basin in the ocean-bottom has here a depth of nearly four thousand fathoms, and the descent to it is by a long and strong gradient." ("Earthquakes in the Light of the New Seismology," p. 258.)

In the Bakerian Lecture to the Royal Society, 1906, Professor Milne treats of great earthquakes and says that "the most active district is at present that of the East Indies." But he also points out the great activity of the region along the Japanese and Aleutian Islands, where the sea is very deep.

Let us now examine the topographic map of the sea-bottom near the Aleutian Islands, as given in the Coast Survey Report for 1900, Appendix No. 7 ("Manual of Tides," Part IV., A, "Outlines of Tidal Theory," by Rollin A. Harris). We notice that along the Aleutian Islands the sea-bottom is sunk down into a narrow trough, which for a considerable distance is over 4,000 fathoms deep, and exactly parallel to the chain of islands. The length of this trough is found to be from thirty to thirty-three times its breadth; and the deeper part is only a continuation of the depression of the shallower. This is shown by the way in which the two troughs, with depths of 4,000 and 3,000 fathoms respectively, fit together, as if one were placed within the other. Moreover the chain of islands is seen to be merely the highest peaks of a mountain range rising just parallel to this deep trough. This range also is about 33 times longer than it is broad, so that if the elevation were shoveled off and thrown into the trough, it would just about fill up the depression, and leave the surrounding sea bottom of nearly uniform depth. By the same method of calculation which was employed in the paper on the cause of earthquakes (p. 311), it may be shown that the probability of this parallelism occurring without a physical basis is

only $1:(10)^n$, where we may put $n=33$. Thus the chances are only one in a decillion that this geometric parallelism would occur without a common underlying physical cause. The coincidence in volume is even more improbable, so that the agreement in direction and in volume, if depending wholly on accidental coincidence, would have a chance of only $1:(10)^{66}$, or one in a decillion decillions. A decillion decillions is practically an infinite number; and it therefore follows that the coincidence in direction and in volume depends on a true physical cause connecting the elevation of the range with the adjacent depression in the sea bottom.

Moreover, after great earthquakes in this region, new islands are frequently raised from the sea, and several new volcanoes have broken out within historical time. Seismic sea waves of the first class frequently follow, the water first withdrawing from the range of islands towards the trough to the south, and then returning later as a great wave. This shows that the sea bottom to the south sinks after the earthquakes by which the region is afflicted. As the islands, and in fact the whole mass of submarine mountains are uplifted by the disturbance, and the sea bottom afterwards sinks, it is evident that lava is expelled from beneath the trough and pushed under the adjacent range. The bed of the sea then gives down to fill up the partial cavity from which the molten rock has been expelled. It will be noticed, moreover, that the trough lies between the ocean and the mountain range, and hence if the leakage of the ocean were the cause of the expulsion of the lava, the subterranean movement necessarily would be towards the mountain range, in accordance with observation.

From this remarkable series of concurrent phenomena, it follows that the chances are literally infinity to one that the trough and ridge are physically connected. It thus becomes an absolute certainty that the submarine mountain range is formed by the expulsion of lava from beneath the trough, that the whole movement is due to the leakage of the ocean, and that it is going on right now; so that the effects observed within historical time are seen to be but a part of the secular process which has crumpled the earth's crust in this complicated manner.

A study of the map of North America shows that the Alaskan mountains to the north of Cook's Inlet are merely a continuation of the Rocky Mountains of Canada and the United States. The Alaskan mountains form the back bone of the Alaskan peninsula and continue into the sea as the Aleutian Islands. The Aleutian Islands are therefore part of the Rocky Mountains still beneath the ocean to show us how the whole system was formed in the course of immeasurable ages. What is here said about the Alaskan mountains running into the sea applies equally well to various other chains of mountains in different parts of the world.

Thus Mr. Caspar Wistar, formerly a student of Professor E. W. Brown, at Haverford College, now at Temuco, Chile, in sending the writer some valuable observations on the Andes, says: "The coast range begins properly about 25 miles north of Santiago, and there is no trouble in following it until it finally disappears in the ocean in Tierra del Fuego and Cape Horn. Lying between the coast range and the Andes is the central valley of Chile. At the northern end is the highest part, where it is close to 2000 feet above sea level; this gradually grows less as one goes south until finally at Puerta Montt it enters the ocean and can be followed on south below the sea level to Smyth's Channel and the western part of the Straits of Magellan."

In like manner the mountains of the peninsula of Lower California are continued under the sea; and dozens of other cases could be cited. These need not be dwelt upon here, as they are already sufficiently familiar to the reader. The case of the Aleutian Islands has been chosen for detailed study, because the mountain forming process is still actively at work there in a way which shows its real character.

The true process by which mountains are formed near the margin of the sea is thus recognized and placed beyond all doubt. Accordingly it follows that the old theories of mountain formation must be entirely abandoned, as having no valid foundation in nature. For owing to the similarity of the effects we cannot suppose that some mountains are formed by one process and some by another. All mountain ranges were near the sea originally, and essentially parallel to the shore; and since the mountains rear their lofty summits

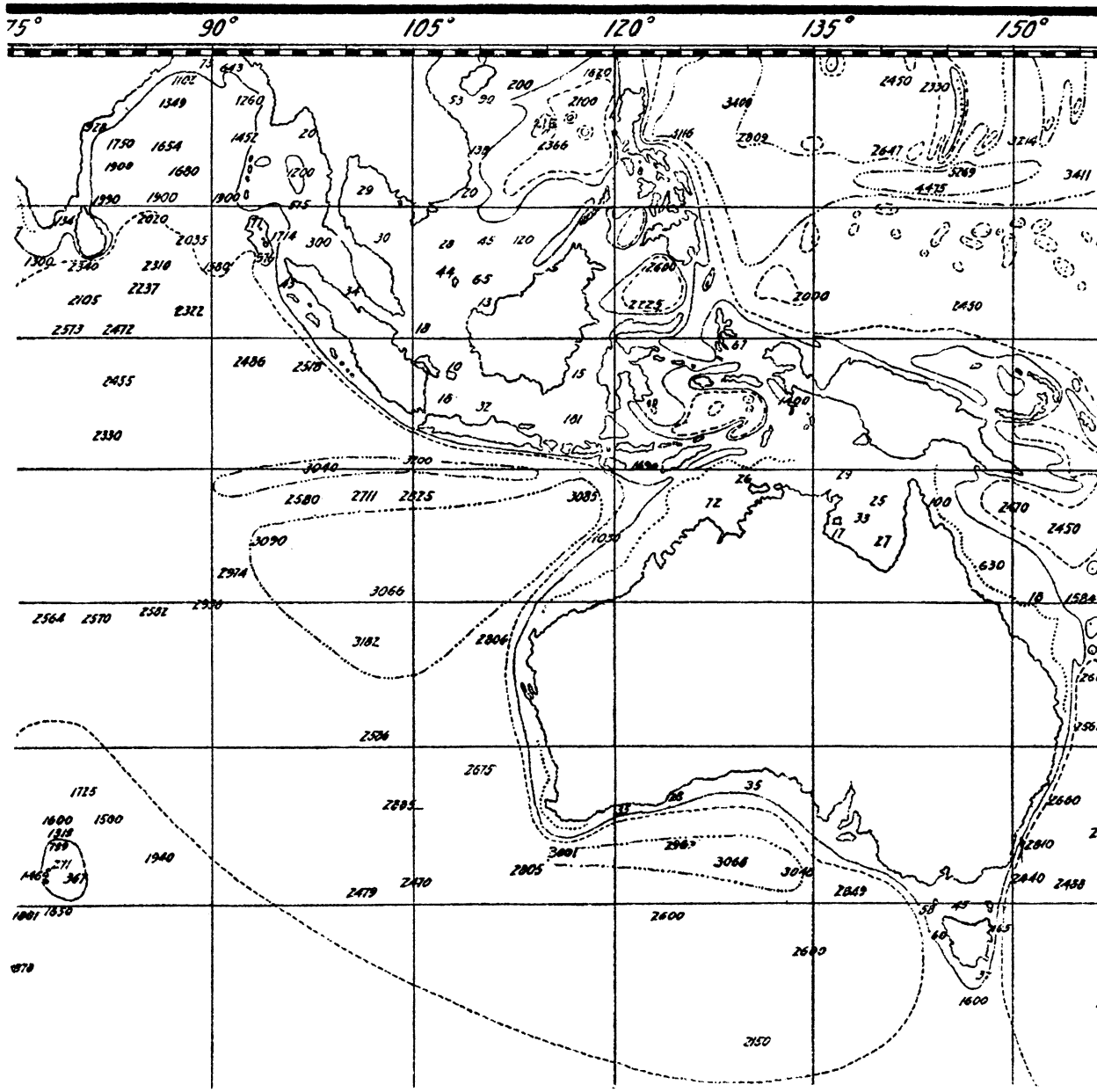
about the sea, as serrated walls around the land, it follows incontestibly that all the mountains of the globe depend on the same cause, which is nothing else than the secular leakage of the ocean bottoms.

Reasoning similar to that here employed could be extended to the deep trenches near the Kurile and Japanese Islands; and by the study of the map of the ocean depths throughout the world one could tell very closely what the state of seismic activity is in any given region. No such digging out of troughs and elevation of adjacent ranges is found to be going on within any continent, and hence it follows that all mountain ranges have been formed by the sea and not at all by the shrinkage of the globe, which obviously is cooling as much in the desert regions as along the sea coasts.

§ 3. *Application of this Theory to Particular Regions of the Ocean Bottom.*—In view of what has been said above regarding the uplifting of ranges in the sea, is it any wonder that volcanoes should break out in the Aleutian Islands? Or, as Major Dutton remarks, that the Russians should connect the earthquakes with the volcanoes of this region? The connection is now established beyond all controversy, and it is shown that the earthquakes are the cause both of the volcanoes and of the mountain formation now going on in the Aleutian Islands.

In Japan the very same cause is at work, and the whole island Empire has been uplifted from the depths of the sea by the injection of lava expelled from beneath the bed of the Tuscarora Deep, which has thus sunk down and developed into the greatest abyss in the world. The true cause of the earthquakes and sea waves by which Japan is afflicted lies in the depth of the ocean to the east of these islands and the resulting leakage and expulsion of lava from beneath it. As the ocean is deepening all the time, this region will always be greatly afflicted by seismic disturbances, and the Japanese people must adapt themselves to the nature of their unstable country, which is still emerging from the depths of the ocean.

It is easy to apply this same reasoning to the East Indies, and hence we see why Java, Sumatra, and other neighboring islands are so afflicted by earthquakes, volcanoes, and seismic sea waves. This region probably is in a more advanced stage of development



COAST SURVEY MAP OF THE REGION OF THE EAST INDIES. In the contour lines 4 points denote a depth of 4000 fathoms, 3 points
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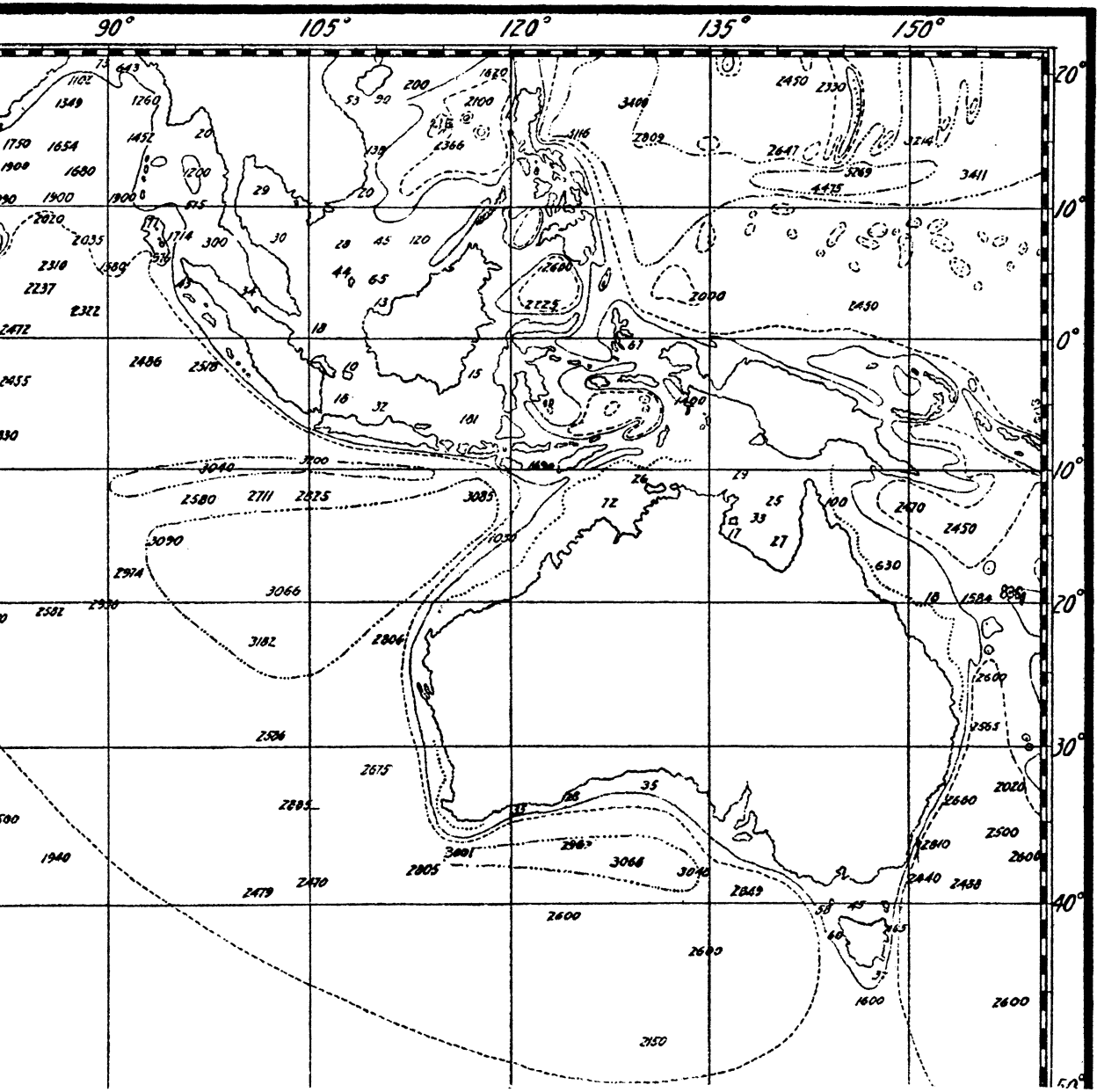

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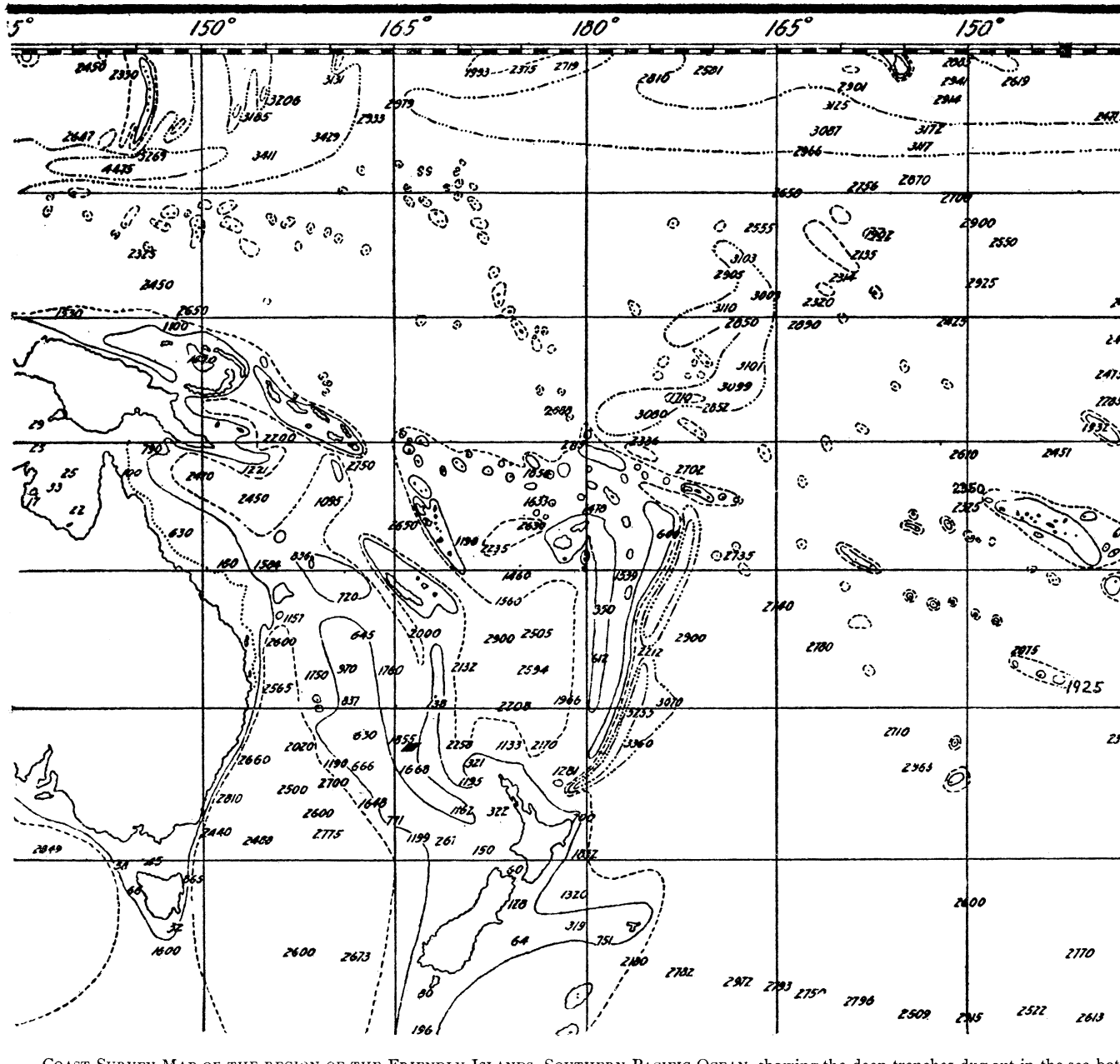

COAST SURVEY MAP OF THE REGION OF THE FRIENDLY ISLANDS, SOUTHERN PACIFIC OCEAN, showing the deep trenches dug out in the sea bot
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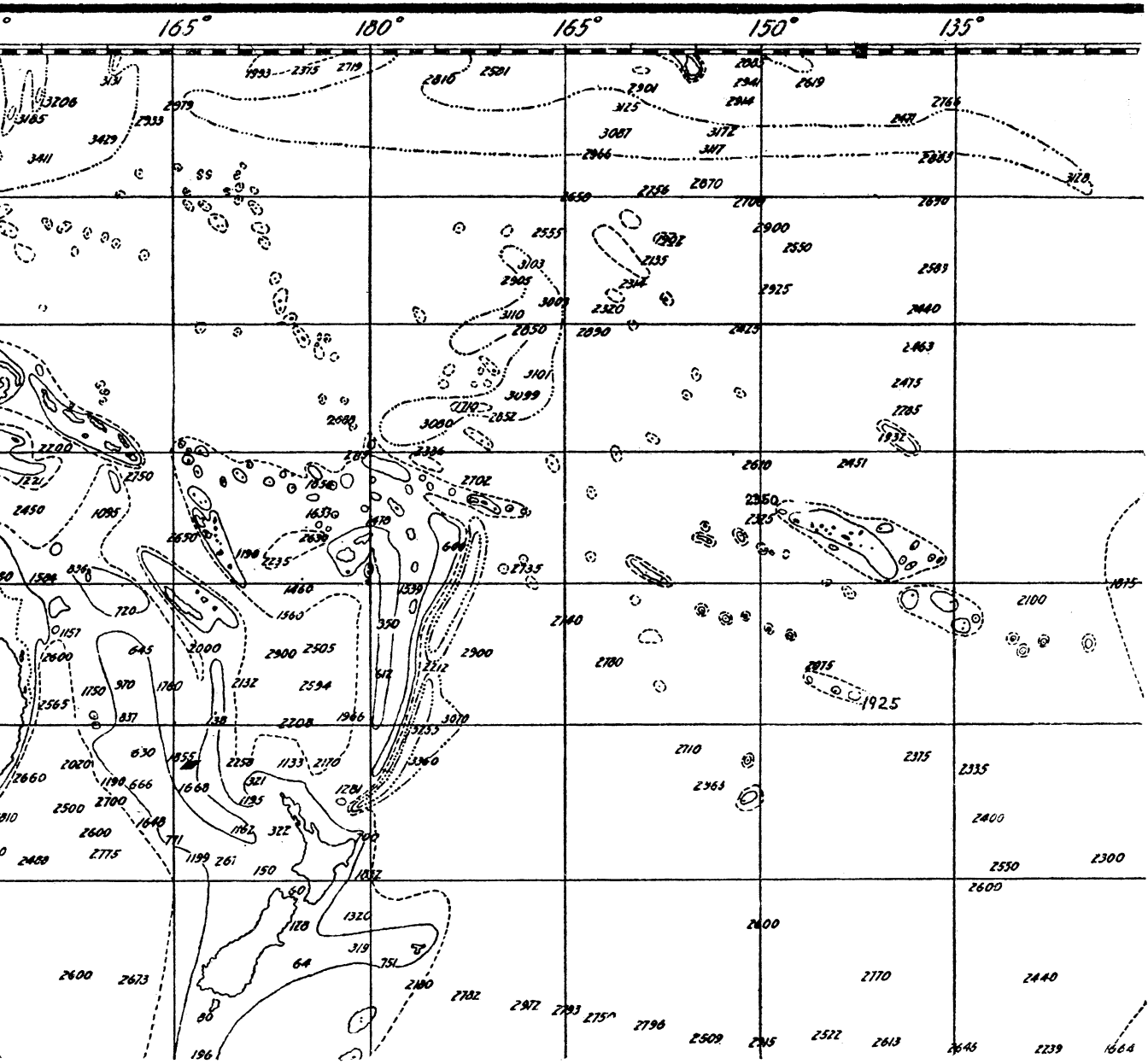

THE REGION OF THE FRIENDLY ISLANDS, SOUTHERN PACIFIC OCEAN, showing the deep trenches dug out in the sea bottom between Samoa and New
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than that of the Aleutian Islands. The latter will eventually connect North America with Asia, and the Arctic will be entirely cut off from the Pacific Ocean. Thus by the study of maps of the ocean depths much light can be thrown upon the past history and present tendencies of the surface of our globe. Even now we may see the formation of islands, mountains and borders of continents still going on. Not only is mountain formation and the uplift of islands going on near the margins of the sea, but, also, at considerable distance from the continents, towards the interior of certain oceans. As a good illustration of this interior development we choose the region of the Friendly Islands in the Pacific between Samoa and New Zealand. Here the water is very deep and the narrow trench is built exactly like that near the Aleutian Islands, having on the west a ridge which has been uplifted by the injection of lava from beneath the trough to the east. The Pacific is here developing a long mountain wall on the west, and it will eventually connect Samoa with New Zealand. The earthquakes and seismic sea waves observed in this region show that the process is going on now, and slowly developing a chain of mountains in the open sea, at some distance from any large continent.

§ 4. *On the Development of Islands and Island Chains.*—In view of the above considerations, it is clear that small islands are essentially mountains under water; and that in the case of large islands the uplifted area was larger, and the bases have since been broadened by the elevation of more land, and the tops flattened by the agencies of wind and water. This was pointed out in the first paper on the cause of earthquakes, §§ 30–38, and attention was called to the lay of the mountains along the centers of the islands, and to the depressions in the bed of the ocean near many of them, due to the sinking of the sea bottom, after the crust was undermined in the process of elevation. By a continuation of the process almost any amount of land could be added. When the uplifted area is of considerable extent, the resulting islands are large, and have flat tops, partly owing to the secular effects of such agencies as wind, water and the leveling action of the waves. Whenever we see a chain of islands in the sea, we know that they are essentially the peaks of a moun-

tain range elevated above the water. A case such as that offered by the Aleutian Islands proves this beyond all doubt; yet in most cases the process of formation has been slow, and the present state of the sea bottom does not show exactly how the development came about. From the study of those islands near which depressions exist we may in time gather much light on the details of island development, and in this way add to our knowledge of the geology of the sea. While the illustrations already given show the general nature of the process, it is clear that the sea bottom is still too little explored to enable us to treat of all cases intelligently, and we must therefore wait for more light as the surveys of the oceans are gradually extended. It is obvious that exact surveys of the sea bottom are needed not only for the laying of cables, but also for the study of the earth's geological history; and the time may come when exact ocean surveys may be as important for our knowledge of the physics of the earth as geological or geodetic surveys of the land.

§ 5. *On the Nature of the Molten Rock Which Moves Beneath the Earth's Crust.*—In the paper on the Cause of Earthquakes we have pointed out the leaky character of the earth's crust, and shown how steam will naturally form in the hot rocks beneath till the lava becomes so fully saturated by this vapor that it swells and requires more space. The steam is not held to be free, but absorbed in the hot rock, causing it finally to expand till it becomes irresistible; and when the elastic tension of this steam-saturated lava becomes great enough the crust begins to shake and the paroxysm continues till it moves along the nearest fault line. When the underlying molten rock has thus obtained more space, the agitation ceases till the tension again becomes too powerful for the crust to withstand, when another readjustment will take place. Thus the process is repeated at successive somewhat irregular intervals of time. The shaking is due to the enforced movement of the molten rock beneath the crust, and the paroxysm thus developed sometimes shakes down cities and devastates whole countries.

A familiar illustration of this process is seen in the lid of a tea-kettle when the steam pressure accumulates till it sets the lid quivering; as the steam escapes at the sides the agitation slowly dies down,

and the lid then remains quiescent till the accumulating pressure again requires relief, when the shaking is renewed. Thus the process is periodic, and the period depends on the rapidity with which the steam is developed. In the case of earthquakes, as already remarked, the steam is not free, but absorbed in the molten rock, and when the agitation begins this gives a similar quivering motion to the block of the earth's crust overlying it, and ceases only when readjustment occurs, usually by the neighboring fault slipping in some way to give more space to the swelling lava beneath. The period is not so regular, as in the case of the tea-kettle, because the resistance to be overcome is never the same in two successive earthquakes; nor is an equal amount of relief afforded even when the underlying force is identical, because the crust moves as soon as its resistance is overcome, and it ceases to move when the displacement is sufficient to restore equilibrium. As the resistances to the blocks of the earth's crust are constantly varying, owing to their complicated mutual relations, and the steam also accumulates at various rates and unequally under different parts, the intervals between successive shocks may be approximately, but are never exactly, equal. Settlements after great shocks, and slight stresses, are relieved by small movements, but eventually the tension becomes great enough to demand a displacement that will provide more space beneath the crust, and then the resulting fault movement usually is conspicuous enough to show at the surface of the ground. The crust is about fifteen or twenty miles thick, and molten lava seldom reaches the surface, except when the crust is uplifted and an outlet facilitated by the opening of cracks, as in mountain chains, which may be along the shore, or in the depths of the sea, projecting above the water as islands. Hence not all islands are volcanic; and by no means all mountains become volcanoes; but such outbreaks frequently happen in the neighborhood of deep seas, where the expulsion from beneath the sea is most violent, and the crust is abruptly and sharply upheaved, so as to afford a chance vent for the imprisoned vapor.

§ 6. *The molten rock beneath the oceans probably experiences an enforced creep towards all available avenues of escape, but the movement usually is not rapid enough to prevent the bottom from*

sinking where the undermining due to expulsion is very active.—This may be inferred from the fact that an ocean such as the Pacific is surrounded everywhere by high mountains, and often by table lands of great elevation. All these mountains and plateaus have been raised from the sea, by injections of lava expelled from beneath the bed of the ocean. The fact, however, that in many places, as along the Aleutian, Kurile, Japanese, and East Indian islands, South America, and elsewhere, the expulsion of lava has been so rapid as to dig out trenches near the ranges of mountains thus elevated, leads one to recognize that in some places the expulsion towards the land is more rapid than the creep of lava from under the sea towards the shore, so that the sea bottom sinks down into a trough. This expulsion of lava happens in a good many places, and the phenomena are clear enough to admit of no doubt. Yet it seems certain that some lava creeps under the crust towards all avenues of escape, along the paths of least resistance, and enforced movements occur in submarine earthquakes. Islands are thus raised in the sea, and where the undermining is rapid the adjacent sea bottom sinks down. Sometimes large plateaus form in the ocean, and slowly rise to the surface, so as to form a large flat island, generally of an elongated type. Submarine plateaus of this kind are now to be found in the north and south Atlantic, and elsewhere, and there can be scarcely any doubt that the leakage of the ocean finds relief by the gradual elevation of such submarine masses, as well as along the shores. The effect of this process is to augment the corrugation of the earth's crust in the course of geological time; and eventually the highest mountains in such submarine ridges rise above the water as islands. On October 16, 1907, a very powerful earthquake was felt all over the world, and the seismographic records located it in the Pacific Ocean between Mexico and Hawaii, about 1,000 miles south of San Francisco. This earthquake seems to have been purely submarine, and even more powerful than those which devastated San Francisco and Valparaiso. It is by such submarine movements that the sea bottom is constantly disturbed and corrugated and crumpled in a thousand ways, and some of the elevations are eventually lifted above the water as islands.

§ 7. *The Effects of Pressure upon the Penetration of Water into the Earth's Crust.*—To judge how effective the pressure arising from the depth of the ocean is in driving the water into the crust of the earth, we may observe first that as water is nearly incompressible for moderate pressures, the tendency to penetrate the rocks is everywhere proportional to the depth of the sea. Thus the deeper the water the greater the pressure and penetrating power. Consequently it is chiefly in the deepest water that we should expect to find the maximum effect arising from the secular leakage of the ocean bottoms. In water of any given depth the pressure is theoretically sufficient to throw a free jet to the surface, if the stream could be made to operate in a vacuum. The pressure in a sea one mile deep would thus throw a stream a mile high; in a sea two miles deep, two miles high; and so on. Now some of the ocean depths exceed five miles, the greatest, near Guam, being 5,269 fathoms, almost exactly six miles. Is it therefore any wonder that the deeps east of Japan, near the Aleutian Island, west of South America, near Guam, between Samoa and New Zealand, give rise to enormous leakage of the sea bottom, and consequently many world-shaking earthquakes? A comparatively feeble pressure of water, such as hydraulic engineers use in mining, rapidly cuts away hills and washes out all their gold; in the same way the waters of Niagara, falling through only 160 feet, slowly wear away the solid rock over which they pour.* What then may be expected of a constant water pressure which will throw a jet five miles high? Such is the pressure all over the bed of the Tuscarora Deep, and it continues from year to year, century to century. It is this pressure which forces the water so rapidly into the earth, and gives rise to all the great earthquakes and sea waves with which Japan is afflicted. No stone on earth, however thick its layers, could withstand such a pressure; nay, under it the water would go through the hardest metals, and sink down deeper and deeper into the bowels

* This analogy with the hydraulic effects of streams of water in motion is not perfect, for the water in the deep seas is merely subjected to great pressure, without bodily movement; yet in both cases the water penetrates the stone to a certain depth. In the one case the water keeps on descending into the earth, in the other the surface particles are carried away by the moving stream.

of the earth. Thus subterranean steam would arise beneath the crust and accumulate till relief was afforded by a shaking of the earth, which gave more space for the saturated underlying molten rock. Hence arise the earthquake belts near the deep seas, where easy relief becomes established in the neighboring crust as it is gradually uplifted into a great ridge or mountain chain.

§ 8. *Explanation of the Instability of Steep Slopes near Deep Seas Noticed by Seismologists.*—Montessus de Ballore and Professor Milne both dwell on the instability of steep slopes near deep seas. The meaning of this is now plain; namely, the slopes become steep by the uplifts due to the expulsion of lava from beneath the deep seas, and the seismic instability arises from this expulsion of lava under the land. The converse proposition for shallow seas is obvious enough, and well illustrated almost all over the world. In some places relief goes on after the seas have become shallow, but there can be scarcely any doubt that the movement started when the water was deeper than it is now. *The world as we find it represents the cumulative effects of physical causes working over vast periods of geological time. And our best rule is to study the typical processes where the water is deep, and the undermining and upheaval so plain as to admit of no doubt. In time we may be able to trace out the history of other unstable regions now in shallow water, or even above the sea level.* No one would now expect to see a range of mountains form far inland, and where such ranges now stand the bed of the sea once encroached. In the course of time the details in the development of such ranges will no doubt be fully worked out, but geology is not yet sufficiently advanced to unravel all that is hidden in the crumpling and folding of the earth's crust. The progress of the next two centuries ought to enable us to write a fairly accurate history of the development of the earth. All the details of particular regions now being gathered would be unintelligible unless analyzed by means of correct underlying principles, and as these have only been established very recently, we content ourselves with outlining correct general ideas, and illustrating the true physicial cause by a few cases which are beyond question. More cases can be added when our knowledge of the world is more developed; but it may require the work of several

centuries to bring out this complex development for all the principal regions of the globe.

II. Causes other than the Secular Leakage of the Ocean Bottom.

§ 9. *The presence of mountain forming processes in the sea, and the absence of such disturbances in the interior of continents excludes the consideration of secular cooling as an active cause in the modification of the earth's crust.*—In the paper on the temperature of the earth we have seen that secular cooling is a very slow and gradual process; and, moreover, it would necessarily operate as effectively for inland as along the sea coasts. Consequently if this cause were real, it ought to produce effects inland comparable to those along the edges of the continents; but the mountains are forming in the sea, and those already completed are distributed along the sea coasts; so that no one would think of ranges now being developed in an interior region far from the oceans. The absence of such mountain-forming processes in the interior of the continents therefore excludes secular cooling as an active agency in the modification of the earth's crust. *The effects of secular cooling could in no case exceed the disturbances noticed in the inland regions, and as these are insensible in regions free from water, it follows that secular cooling is not a true physical cause of mountain formation and kindred phenomena. Consequently this cause is not now and never has been active in modifying the crust of our globe.*

§ 10. *The Untenability of the Theory that World-Shaking Earthquakes Arise from the Snapping and Bending of Rocks.*—In view of what has been established in this series of papers, it is difficult to see how any one could again ascribe world-shaking earthquakes to the bending and snapping of rocks under stresses arising from the progress of secular cooling. If this is the cause which is at work, why should the great seismic disturbances occur chiefly in or near the oceans, and especially where the sea is deep, while inland regions remain quiescent? By no possible stretch of the imagination can these movements be traced to the secular cooling

of the terrestrial globe. For, if so, how are we to explain the digging out of ocean trenches and the elevation of the adjacent crust into a mountain range, as often happens in the depths of the sea? If any kind of wrinkling due to secular cooling were at work, it seems certain that the inland regions could not escape the same influence.

The difficulty experienced in accounting for the vibrations of the great earthquake at San Francisco, on the hypothesis that a rock had snapped or slipped, is thus fully sustained. If such a cause had given rise to the earthquake, the vibrations would have been of simpler character, accompanied by less rotatory motion, and the whole disturbance would have been less violent and of much shorter duration. It may be asserted with confidence that no vibrations arising from the snapping of rocks would have been sufficiently powerful or long continued to shake down cities and spread universal devastation over the land. Above all, such effects of secular cooling could not explain a general phenomenon like the uplifting of the mountains as veritable walls about the margins of the sea. Nothing but the expulsion of lava from under the sea would be adequate to account for this upheaval of the crust, and it is hard to see how any thing but the shaking incident to this enforced and prolonged subterranean movement could devastate the land and disturb the whole world. In the expulsion of lava from beneath the sea, the true cause of earthquakes is clearly recognized, and all the most important phenomena connected with the physics of the globe are correctly assigned to the secular leakage of the ocean bottoms, which necessarily is greatest where the sea is deepest. This hypothesis alone is adequate to account for all the phenomena of nature. The unity and harmony and mutual dependence shown to exist among the most diverse phenomena observed at the surface of the earth is the best proof of a common underlying cause, and such a theory will strongly commend itself to the natural philosopher who seeks in the abundance and variety of nature indications of a single fundamental law.

How great is the change in the new point of view may be seen from the following discussion by Professor J. W. Gregory, taken from the "London Sunday at Home," 1906:

"A volcano is a pin-prick in the earth's surface and it serves to relieve the local pressure by permitting the escape of steam and molten rock; but an earthquake is produced in most cases by a sudden fracture of the solid substructure of a large region, and as the great mass of material slips into a new position, the shock causes the crust of the earth to shiver from pole to pole. These dislocations are naturally most frequent in regions where mountain ranges are apparently still being squeezed up—where rocky folds are still being bent into shape, as in the Himalayas, and off the west coast of North and South America, and the North of Japan. Regions of greatest instability of the earth's crust are, in fact, found chiefly along the margins of continents or tablelands which rise suddenly to considerable heights above oceanic or other plains. Comparatively few earthquakes have their origin near to volcanoes, and the general belief that all great earthquakes are due to volcanic eruptions is not supported by evidence derived from observations."

Professor Gregory thus says that earthquakes occur chiefly where mountain formation is in progress, but he is entirely silent as to the cause of mountain formation itself. Unfortunately he blindly accepts the traditional doctrine of the secular cooling and contraction of the globe, which is shown to be devoid of any sound physical basis.

§ 11. *An Estimate of the Relationship between the Expansion and Contraction of the Globe.*—It is well known that at intervals the sea coasts are elevated by the world-shaking earthquakes to which they are subjected. It is difficult to form an estimate of the total area thus uplifted, but for a preliminary estimate we may take it to have an average extent of 200 miles square, which would about correspond to the phenomena witnessed in the greatest earthquakes. There would be 4,924, or roughly 5,000, such areas on the surface of the entire globe. According to Milne's estimate of 60 world-shaking earthquakes per annum, there would be 120,000 in the 2,000 years which have elapsed since the century before the beginning of our era.

Now an examination of great earthquakes shows that about one in four is accompanied by a sensible elevation of the disturbed area. If there are in all 5,000 such areas to raise, and 30,000 disturbances for raising them, it follows that on the average, when all areas are affected alike, each part would be raised 6 times in 2,000 years. An average raise of 2 feet is not extreme, and this gives an expansion of the total surface of the globe amounting

to 12 feet in this period. In the paper on the temperature of the earth, p. 286, we have shown that the shrinkage due to cooling in 10 million years, according to Daniell, would not exceed 612 feet; and, taking this effect to be uniform, the shrinkage in 2,000 years would be only 0.12 of a foot, or exactly 0.01 part of the calculated elevation due to earthquakes. Now in the above calculation of the expansion due to earthquakes, we may have taken the disturbed area too large; but one uplift in four great disturbances does not seem to be an over estimation of the effects of elevation. The sinking of the sea bottom, however, goes on, and less frequently the land along the shore is carried down also; and possibly the elevation is relatively less than we have computed. As this calculated expansion is 100 times the shrinkage, we might reduce the size of the uplifted areas to 100 miles square, and still the expansion would exceed the contraction by 25 times. We could again reduce the areas to 50 miles square and make the uplift over 6 times the contraction. If, however, the uplifts be restricted to the areas covered by the land, the effect would be quadrupled. To make the expansion just equal to the contraction we should have to reduce the amount of the average vertical uplifts from 2 feet to 1 inch, or make the 2-foot uplifts 24 times less frequent, so that only one would occur in 96 great earthquakes.

This seems to be excessively small, and I think it practically certain that the expansion of the globe is from 10 to 100 times more rapid than the contraction, in the evaluation of which we have used Daniell's maximum estimate.

When we contemplate the mountains and plateaus, we see that an expansion of our globe is indicated by its general aspects. For it is in this manner that the mighty mountains have been upraised, and the vast plateaus uplifted, without greatly depressing large areas of the sea bottom. As the earth is almost totally devoid of shrinkage due to secular cooling, the maximum estimate being 1.44 inches in 2,000 years, this most probably indicates a secular expansion of our planet. In any given age the expansion is not equally effective all over the terrestrial spheroid, but the present distance of many mountains and plateaus from the sea shows that

it goes on steadily, and in times gives rise to large effects over considerable belts. It seems therefore practically impossible to avoid the conclusion that our earth is not contracting at all, but on the contrary is actually undergoing a slow secular expansion. In any given geological age the areas uplifted may be confined to particular regions, chiefly along the sea coasts, but in the long run it will include a large part of the earth's surface. In the course of ages more and more land is raised above the sea, which at the same time is contracting its extent and decreasing its total volume by the secular desiccation arising from the gradual absorption of the waters into the rocks of the earth.

§ 12. *Researches Founded on the Hypothesis of the Gravitational Instability of the Terrestrial Spheroid Rest on a False Premise.*— Quite recently several of the most learned mathematicians in England have treated of the uplift of the continents and their secular movements, on the hypothesis that these effects are due to gravitational instability in the progressive shrinkage of our planet. It is scarcely necessary to point out that in order to reach correct conclusions we must start from correct premises, as well as follow an unbroken chain of reasoning. One may readily concede that the learned discussions which have appeared from several eminent investigators are perfect specimens of the logical art, and adorned with flawless mathematics. But if the premises are not well founded in nature, the superstructure built thereupon necessarily falls to the ground. It does not seem to have occurred to these learned investigators to examine critically the underlying premises, for no doubt they assumed the historical doctrine of secular cooling and contraction of the globe as unassailable.

From our study of this question, however, it seems certain that the earth's cooling is infinitely slow, and that no sensible contraction or other movements depend on this cause. The observed movements are always near the sea, which shows that they depend in some way upon the oceans. As the land is frequently upheaved along the sea coast, and all the mountains and plateaus have been thus uplifted, it is impossible for such movements to depend upon the mere settlement of a gravitationally unstable planet. Hence in the present en-

crusted state of the earth we must reject the whole doctrine of secular shrinkage as false and misleading.

As the earth was once of larger volume and smaller density than at present, there may have been a time when it was settling owing to gravitational instability, *but this was long before the surface had become encrusted.* Since the consolidation began the cooling has been excessively slow, and no convective circulation has taken place within; consequently the planet has not since experienced any sensible gravitational instability, except that due to earthquakes arising from the penetration of water vapor, which gives rise to mountain formation and kindred phenomena now witnessed at the surface of the earth. The theory of gravitational instability as applied to the earth therefore is not valid, because it applies to a far earlier stage in our history, before the crust had begun to form. The premise underlying this learned reasoning seems therefore false, and we can only look upon such an ingenious speculation as an interesting example of brilliant abstract reasoning, in no way applicable to the present or recent history of our planet. By no possibility could such theories enable us to explain the distribution of earthquakes, or their prevalence near deep seas, where trenches are being dug out in the sea bottom and mountains uplifted along the borders of these abysses.

What is said here in regard to these several investigations applies also to Professor Love's learned discussion of the gravitational instability of the earth, involving the various orders of spherical harmonics. His beautiful mathematical theory is a monument of ingenuity, correct on the hypothesis, but the latter is lacking in physical basis, and consequently the investigation is chiefly valuable as a piece of abstract reasoning of high order, interesting in dynamics, but not applicable to the development of our actual earth.

§ 13. *Views of the Late Professor James D. Dana on Mountain Formation.*—Among the many eminent geologists who have treated of mountain formation, the late Professor James D. Dana stands preëminent for having come nearest to the correct theory; and although the false hypothesis of the contraction of the earth underlies his views and vitiates them, yet they are sufficiently remarkable

to deserve the attention of the careful reader who seeks to follow the historical development of human thought. It is only by a survey of this kind that one gets an adequate perspective of the theories developed in the different ages. Dana's views are given in his "Manual of Geology," 1863, and the most interesting passages are the following:

(*A*). On page 29, he points out that the continents are all walled in by mountains erected about their borders, and adds:

(*a*) "The continents thus exemplify the law laid down, and not merely as to high borders around a depressed interior—a principle stated by many geographers—but also as to the highest border being on the side of the greatest ocean (first announced in *American Jour. Sci.* (2) XVII, vols. III, IV, 1847, and XXII, 335, 1856). The continents then are all built on one model, and in their structure and origin have a relation to the oceans that is of fundamental importance."

He also observes that the borders of continents are from 500 to 1,000 miles wide, and infers that "a continent can not be less than a thousand miles (twice five hundred) in width," otherwise it would not have the characteristic basin form with mountain barriers about a low interior.

(*b*) On page 731 he discusses the evolution of the earth's great outline and reliefs, and of the successive phases in its progress, summarizing his conclusions as follows:

I. "The continents have mountains along their borders, while the interior is relatively low; and these border mountain chains often consist of two or three ranges elevated at different epochs."

II. "The highest mountain-border faces the largest ocean, and conversely."

III. "The continents have their volcanoes mainly on their borders, the interior being almost wholly without them, although they were largely covered with salt water from the Azoic age to the Tertiary. Also metamorphic rocks later than the Azoic age are most prevalent near the borders."

IV. "Nearly all of the volcanoes of a continent are on the border which faces the largest ocean."

V. "The strata of the continental borders are for the most part plicated on a grand scale, while those of the interior are relatively but little disturbed."

VI. "The successive changes of level on coasts, even from the Azoic age to the Tertiary, have been in general parallel to the borders of mountain chains; as those of the eastern United States, parallel to the Appalachians, and those of the Pacific side, as far as now appears, parallel to the Rocky Mountains."

VIII. "The continents and oceans had their general outline or form defined in earliest time. This has been proved with regard to North America from the position and distribution of the first beds of the Lower Silurian—those of the Potsdam epoch. The facts indicate that the continent of North America had its surface near tide-level, part above and part below it (p. 196), and this will probably be proved to be the conditions in Primordial time of the other continents also. And, if the outlines of the continents were marked out, it follows that the outlines of the oceans were no less so."

The three other conclusions announced by Dana are of less interest, and need not be quoted here.

(*B*). The following deductions (p. 732) regarding the positions of the reliefs are of high interest:

"1. The situation of the great mountain chains, mainly near the borders of the continents, does not indicate whether the elevating pressure acted within the continental or oceanic part of the earth's crust. But the occurrence between the principal range and the seacoast of the larger part of the volcanoes (and, therefore, of the profound and widely-opened fractures) of these borders, of the most extensive metamorphic areas, and of the closest and most numerous plications of the strata, as so well shown in North America, are sufficient evidence that the force acted most strongly from the oceanic direction."

"2. The relation between the extent of the oceans and the height and volcanic action, etc., of their borders proves that the amount of force in action had some relation to the size and depth of the oceanic basin. The Pacific exhibits its greatness in the lofty mountains and volcanoes which begirt it."

"3. In such a movement, elevation in one part supposes necessarily subsidence in another; and, while the continental was the part of the crust which was elevated, the oceanic was the subsiding part."

In connection with the theory that the mountains are formed by the expulsion of lava from beneath the sea, through the operation of world-shaking earthquakes, these early views of Dana are of great interest. But in other respects he was led astray by the doctrine of the secular refrigeration of the globe; for he says that "no other cause presents itself that can comprehend in its action the whole globe and all time." He thus speaks as if the entire globe were shrinking, whereas local changes only are occurring, and these always near the sea. Dana's view that "the pressure of the subsiding oceanic portion has acted against the resisting mass of the continents; and thus the border between them has become elevated, plicated, metamorphosed and embossed with volcanoes," is alike

misleading and unjustifiable. For to produce such an effect the settling of the ocean basin would have to be many miles, and we have shown that no such shrinkage has taken place since the crust was formed; on the contrary there is reason to think that the earth is expanding at a rate of from 10 to 100 times that of the contraction due to secular cooling. Moreover we have no more right to assume that the continent is squeezed by the settling of the ocean, than that the ocean is squeezed by the settling of the continent.

We have, however, recalled these views in order to do justice to the most original of the older American geologists, and also to let the student see where he departs from the true line of thought. Many years ago Rev. O. Fisher showed that shrinkage was wholly inadequate to account for the height of the mountains observed upon the earth, which are hundreds of times higher than the contraction theory will explain. In the paper on the cause of earthquakes it is shown that the contraction theory is also emphatically contradicted by the present distribution of mountains. In the present paper and that "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," it appears that at present the earth is not contracting at all; so that we are compelled to abandon the older theories entirely.

As heretofore developed geology has presented the strange anomaly of offering no theories adequate to account for the uplift of mountains and plateaus or the deposits of fossil beds thousands of feet above the sea. This is the more remarkable, since in the days of Humboldt, Lyell, and Darwin, the bodily elevation of the land was an accepted item of belief. But subsequently Lord Kelvin, Sir George Darwin, and other eminent British physicists, showed, from the investigation of tidal and other phenomena, that the earth as a whole behaves as a solid; and under the influence of this line of thought geologists gave up the doctrine of the bodily elevation of the land, and restricted themselves to the collapse of portions of the crust under gravity. The theory of collapse, however, utterly fails to explain mountains and plateaus and islands, as well as shells and other organic remains at great height above the sea level. But it was felt that the argument of the physicists against the bodily

yielding of the earth was unanswerable, and so it is for the globe as a whole; yet this does not disprove the existence of a layer just beneath the crust which in earthquakes behaves as fluid*

In the present researches a theory is developed by which these two views may be reconciled, and it is, I think, clearly proved that in earthquakes there is movement of molten rock beneath the earth's crust. It is this movement of molten rock beneath the crust which produces most of the dislocations, crumpling, folding, and fault phenomena studied in geology. If such a theory is justifiable, it shows us how cautious we must be in drawing final conclusions, and how incomplete all the sciences still are to-day.

§ 14. *Criticisms of the Theory here Adopted.*—Not many criticisms of weight have reached the writer since the publication of the papers on the "Cause of Earthquakes" and the "Temperature of the Earth," but he may here notice two to which some attention may be given.

1. *A geologist thinks that the absence of volcanoes about the South Atlantic is difficult to explain.* This supposed difficulty is much less real than it seems; for some submarine volcanoes have been known in that region, and a good many submarine earthquakes. The sea is shallow near the borders, but a long tableland is rising in the center, and we have no means of knowing how many disturbances occur in this region, which is comparatively seldom visited by ships. Probably the lava finds an avenue of escape under this submarine plateau, and some sea waves occur from time to time, but the region is too far from land to produce great inundations of the shore. As the land is not yet lifted into a sharp ridge, the mountains do not yet appear above the water, and such eruptions as occur beneath the

* Since this was written Professor Wiechert of Göttingen has presented to the International Seismological Association in session at the Hague, Sept. 21–26, 1907, a report of the chief results of his researches on the internal constitution of the earth. The existence of long vibrations in the tremors propagated by earthquakes, with periods of eighteen seconds or more, reveals, he thinks, the presence of a layer of liquid or plastic material at a depth of about thirty kilometers from the surface. (See report of meeting by Professor Harry Fielding Reid in *Science,* Jan. 10, 1908.) Note added Jan. 22, 1908.

sea pass unnoticed. It is not remarkable, therefore, that we find so few volcanoes in this region, and the absence of known volcanoes in no way contradicts the theory. Volcanoes usually break out after mountain ridges are folded sharply upward; this stage may come later in the South Atlantic, where the sea is neither very deep nor the gradient very steep near the shores. Consequently in such a region we should not expect at present many volcanoes or great visible earthquake effects.

2. *Some geologists have believed also that the steam escaping from volcanoes comes from the central magma of the globe.* But if this were true, as we have pointed out in the paper on the "Temperature of the Earth" (p. 288), the volcanic outbreaks ought to occur in the interior of the continents as well as near the oceans. For the vapor ascending from the central magma of the globe could not always be deflected around the immense extent of the continents, and appear only at their edges, and in the depths of the sea. The geographical distribution of volcanoes therefore effectively contradicts any such hypothesis.

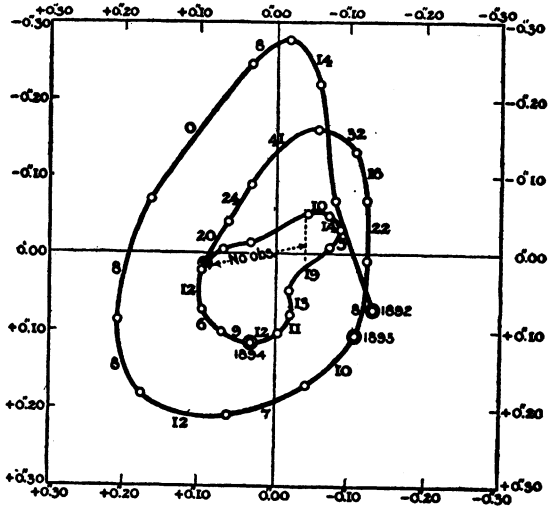
§ 15. *The Criticism based on the Supposed Coincidence of Great Earthquakes with the Sudden Shifting of the Earth's Axis in its Revolution about the Mean Axis of Figure.*—A reviewer of the paper on the "Cause of Earthquakes," in *Nature,* August 1, 1907, after admitting the adequacy of the cause assigned to explain most phenomena finally adds:

> "But his (See's) explanation fails to account for the remarkable connection between the irregular shifting of the earth's axis and the occurrence of the greatest earthquakes. That these irregular movements of the axis are greatest when large earthquakes are most frequent is a certain, but as yet unexplained, fact; it seems to necessitate displacement of matter in the earth on a far larger scale than is indicated by the differential measurements which alone are open to us. Professor See's explanation, though it provides for lateral and vertical displacement of matter, necessitates the elevations and depressions being so closely contiguous as practically to neutralize each other's effects, and, therefore, fails as an explanation of the ultimate cause of earthquakes, while it in no way affects the current acceptance of fracture as their immediate cause."

This criticism is not well founded, and after what has been said above and in the two preceding papers, probably does not require

any elaborate notice; yet we may briefly point out the weakness of the position taken, which seems to be the same as that announced by Professor Milne in his Bakerian Lecture to the Royal Society, 1906, where he says:

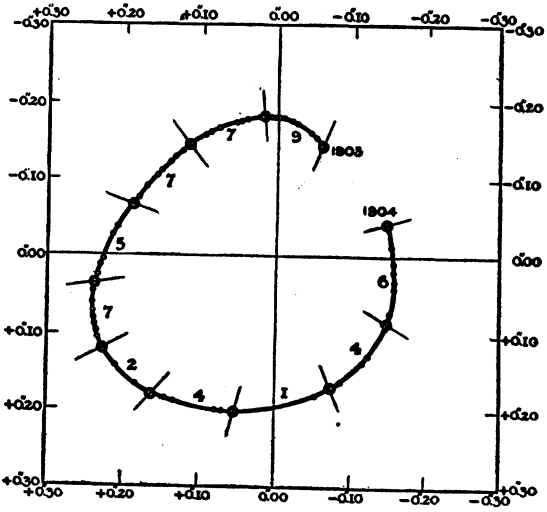
"If we take a chart showing the varying position of our earth's north pole in relation to its mean position, we see that the secular movement of the pole is by no means uniform. Although it may at times follow a path about its mean position which is approximately circular, at other times there are comparatively sharp changes in direction of motion which may even become retrograde. If now on a chart of this description we mark the time positions of very large earthquakes, we find that they cluster around the sharper bends of the pole path." (See the accompanying figures with explanations taken from Professor Milne's paper.)



"FIG. 1. After Th. Albrecht. The path of the North Pole from 1892 to 1894 inclusive. Each year is divided into tenths or periods of 36.5 days. Numerals indicate the number of large earthquakes which occurred in each of these divisions, commencing with the third tenth of 1892."

"In a period of nearly 13 years (1892 to 1904) I find records for at least 750 world-shaking earthquakes, which may be referred to three periods continuous with each other, and each two tenths of a year or 73 days' duration. The first period occurs when the pole movement followed an approximately straight line or curve of large radius, the second equal period when it was undergoing deflection or following a path of short radius, and the third when the movement was similar to that of the first period. The numbers of earthquakes in each of these periods taken in the order named were

211, 307 and 232, that is to say, during the period when the change in direction of motion has been comparatively rapid, the relief of seismic strain has not only been marked, but it has been localized along the junctions of land blocks and land plains where we should expect to find that the effect of general disturbances was at a maximum. It can hardly be assumed that the



"FIG. 2. This is similar to Fig. 1, but refers to the year 1903, during which period the pole displacement was more uniform than that indicated in Fig. 1."

frequency under consideration is directly connected with change in direction of pole movement; but it seems not unlikely that both effects may arise from the same redistribution of surface material by ocean currents and meteorological causes generally."

This reasoning of Milne asserts that the greatest earthquakes occur when the path of the pole bends most rapidly. In reply to this claim we may remark in the first place that it is very doubtful whether a general law of this kind can be fairly deduced from existing observations, because the path of the pole depends on such minute quantities that the curvatures platted may not be real. In the second place, if the assumed law were admitted, the meaning of it would still be open to interpretation, and several of these could no doubt be made without involving a contradiction of known laws.

For the total displacement of the pole from the mean position is nearly always less than 30 feet, and generally less than 15 feet;

these movements correspond to quantities represented in arc by 0″.30 and 0″.15, which are on the very limits of our most accurate astronomical measurements. The apparently sharp turns in the pole path, therefore, may not be real, but merely a delusion arising from some unknown cause. If, however, these sharp turns are real, this fact cannot be certainly established till the polar motion has been repeated many times, and the data now available do not seem sufficient for this purpose.

Moreover, even if the sharp turns are real and it could be proved that the great earthquakes gathered about them, in regard to which there is still much doubt, our interpretation of the results would be open to much uncertainty. For it could not be inferred that large masses of matter are in motion within the earth, and that the displacement of these masses causes a sudden change in the movement of the pole. We have seen that the matter of the earth's interior is kept rigid by pressure, and that no movement deep down in the globe ever takes place. This is shown by the fact that a shock originating deep down would be felt with moderately uniform intensity over a large area, which is disproved by observations showing that all great earthquakes are quite superficial. If no shocks originate at great depth, the only other possible movement would be just beneath the crust; and it is quite impossible that currents could move for great distances just beneath the surface without disturbing the whole intervening region of the globe.

Much as has been done on this difficult subject by the greatest mathematicians, it is not yet known what causes operate to displace the pole from the mean axis of figure, and maintain the displacement in spite of friction and viscosity; but recurring seasonal effects, together with the imperfect rigidity of the earth, have been generally accepted as the chief causes. Is it not, therefore, probable that whatever displaces the pole and thus maintains its revolution about the mean pole, according to the Eulerian Theory as modified by viscosity and imperfect rigidity, may suffer variations through combinations of storms, and other atmospheric and tidal agencies? And that these combinations of varying stresses operate to bring on earthquakes where instability of the crust already exists, from the accumulation of subterranean steam pressure?

These combinations of circumstances are not the dynamical *cause* of the earthquakes, but only the *occasion* for outbreaks when instability is already developed. It might thus be that earthquakes would break out when the polar motion is changing most rapidly, *but the earthquakes do not cause the change; rather they are occasioned by that which makes the change.* Milne's view above quoted does not seem to differ much from this, for he says that "both effects may arise from the same redistribution of surface material by ocean currents and meteorological causes generally," though he overlooks the leakage of the oceans as the cumulative dynamical cause of instability.

On these grounds probably very few will agree with Professor Milne, if he is the reviewer quoted in *Nature,* that the present explanation fails. The facts which he assumes are not proved, and even if they were, the interpretation should be exactly the reverse of that which he has given in *Nature.* Consequently we may dismiss this whole criticism as not well taken. Nothing is more certain than that movements of large masses within the earth adequate to displace the polar motion do not take place. A supposed effect of this kind is contradicted by all that we know of the rigidity and solidity of the earth under pressure of its own mass, which would prevent deep movements, and by the well-established fact that all earthquakes are shallow and the shock limited to one locality. Movements in the sea and in the atmosphere, however, might conspire to displace the pole and vary its rate of movement about the mean position, and the stresses thereby exerted upon the globe might occasion seismic outbreaks where the steam pressure had already approached the limits of stability. If the facts assumed by Professor Milne, are confirmed by time and experience, it is in this way that they must be explained; the outbreak of earthquakes being *occasioned,* but not *caused,* by the surface movements of water and air which displace the pole from its mean position and vary its rate of movement in different parts of the path, and thereby also the stresses exerted upon the different parts of the already unstable revolving globe.

§ 16. *On an Explanation of the Squeezing up of the Continents by the Settlement of the Ocean Basins given in Some Works on*

Geology.—In the work on "Geology" by Chamberlin and Salisbury, Vol. II., p. 129, we find the following curious figure and explanation of the elevation of the continents:

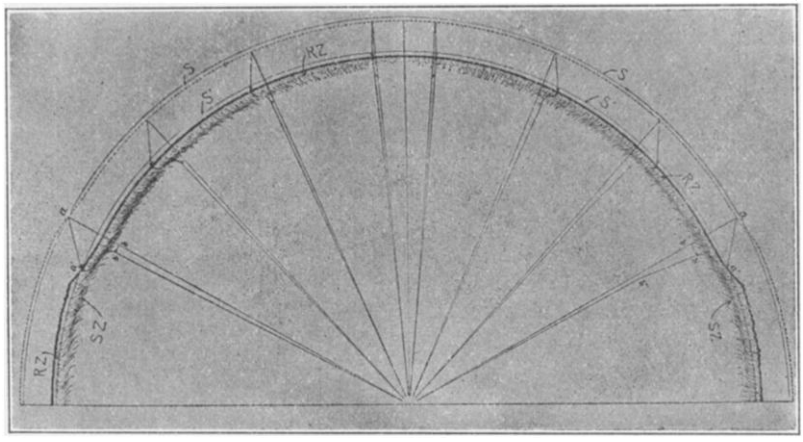


FIG. 3. Illustration of general deformative movement, from Chamberlin and Salisbury's "Geology," Vol. II., p. 129.

"FIG. 32 *C*. Diagram illustrating the supposed elements of a general deformative movement. *SS* represents the outline of the sphere at the ocean level before deformation. The dotted line represents the corresponding surface of the lithosphere, the ocean basin occupying the center and the continents the flanks. *S'S'* represents the outline of the sphere at the ocean level after deformation, the heavy line representing the outer surface of the deformed lithosphere, and the space between *SS* and *S'S'* representing (much exaggerated relatively) the vertical shrinkage which is the great feature of the movement but is only made apparent through its deforming effects. That part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent. The central portion beneath the ocean is represented as descending directly toward the center. The portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines, of which those at the border of the ocean, *a, a'*, are the most oblique and represent the greatest thrust. On the borders of the continent the crust is folded to the extent of this lateral thrust. This of course only holds true when the thrust is limited to a single oceanic basin. The lateral thrust is chiefly felt in the outer shell or rigid zone, *RZ,* which embraces the heavy line and the dotted zone below. Beneath this lies the shear zone, *SZ,* whose foliated structure is represented as not unlike that of the 'drag' belt of a fault plane. The igneous sheets, batholiths, etc., which are supposed to especially affect this zone are not represented. The great

sector beneath the ocean is represented as having crowded slightly upon the sectors beneath the continents on either hand, this crowding being represented by the short arrows *b, b'*. By comparing *bb'* with *aa'* the reason for the shear zone will be made apparent. On the right-hand side the outer part of the sub-oceanic sector is represented as crowding upon the continental sector an exceptional amount, as represented by the deflection of the line *b'b''*. This gives rise to the plateau at the right. The proportions of most of the significant parts are necessarily exaggerated relatively."

Let us now analyse this explanation a little more closely. These authors remark that "that part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent." Is not this a purely gratuitous assumption, simply begging the question, and wholly unjustifiable? Why should the oceans descend without compression, while the continents are squeezed up at their edges? Obviously one has as much right to assume that the oceans are compressed by the sinking of the continents, as that the continents are compressed by the sinking of the oceans. Again, they say that "the portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines, etc." But does not the assumption that "the portions preserve their length" imply that the ocean segment has not shrunk at all in respect to surface area, while the continent has been squeezed up at the edge to let it go down?

What right have we to assume a similar shrinkage in the radius of these sectors, and admit a shrinkage in one surface area (the continental) but deny it in another (the oceanic), which is much the larger of the two?

Could one imagine a more improbable effect of secular cooling?

Moreover the above figure corresponds to a shrinkage of about one tenth of the radius, or 400 miles. In view of the fact which has been shown in the paper on the "Temperature of the Earth" that our globe is not shrinking at all, it is unnecessary to make further comment on this unauthorized procedure.

But we may remark that in this "Geology," Vol. II., p. 131, we find a direct contradiction of the above explanation. It runs as follows:

"The continents now rise about 3 miles above the average ocean bottom, and much more than that in certain portions. Since the volume of the ocean has probably not greatly changed during known geological time and since the continents appear to have risen above surface, about as now, in the earliest known geological ages, it is assumed that similar differences of relief have prevailed at the various known deformative periods. We have seen that the gravitative pressure at 3 miles' depth is nearly or quite as great as the shearing-resistance at that depth. If a shearing-zone at depths of 3 to 5 miles had already been developed during the primary deformation, this would facilitate a reversed movement along the same shear-planes. It is therefore conceived that the continental platforms, by pressing upon their bases to the extent of 16,000 to 30,000 pounds to the square inch, would, though opposed by perhaps 5,000 pounds per square inch pressure from the oceans, gradually creep laterally under their own gravity, in a slow glacier-like way. This supposed lateral creep should be attended by crevassing, fissuring, and normal faulting; in other words, *by the prevalent tensional phenomena which the continents present.* It should be much more marked in the plateau regions than elsewhere, because of their superior elevation, and it is there that normal faulting is most pronounced."

Thus in one place we are assured that the continents have been squeezed up, in another that they are creeping down in a slow glacier-like way. If they are creeping down how were the mountains elevated? And why should these uplifts appear at the borders of the continents? Perhaps it will be answered that these two movements are going on together. But does not the first principle of the new theory tell us that neither of these supposed movements has any reality, and that the mountains and plateaus are elevated by the expulsion of lava from beneath the sea, the shells of which are thus carried to the greatest height in the gradual uplift of the land?

§ 17. *On the Folding and Distortion of the Strata seen at the Earth's Surface.*—In many works on geology the crumpling and folding of the strata are attributed to "a gentle warping of the soil." No doubt where mere settlement of the ground is in progress, owing to undermining, there is some warping of the soil; but this implies that the strata have already been uplifted and undermined, so as to become unstable. Such uplifting is the work of earthquakes, during past geological ages, though the settlement and warping may be due to the gradual undermining effects of water or other agency which produces instability. All movements of this kind are of small importance compared to the greater and more violent

derangements due to earthquakes. Many of the dislocations of the strata now seen on land originated when they were beneath the sea, and it would be a mistake to attribute any considerable part of these movements to seasonal or meteorological influences. It may be that the shape of the two sides of a valley undergoes an infinitesimal deformation from these causes, yet no important effects depend on such small deformations. They are all very superficial in character, whereas the causes which have folded the rocks of the earth's crust have been much more deep seated, and originate principally in earthquakes. When we see folded strata laid bare by erosion therefore we may assign the greater part of such effects to the " gentle warping of the soil " experienced in the dreadful shakings and derangements due to earthquakes of the world-shaking class. In observed plications of the strata earthquakes have supplied the principal part of the disturbing force. The important uplifts have all arisen in this way, and the instability thus resulting has produced the smaller displacements noted where the earth is settling.

The ground is more or less flexible near the surface, and sensible sagging may be produced by loading, but such effects are shallow and small in amount, and it would be a mistake to attribute to this cause important deformations of the strata. Is not such phraseology as the " gentle warping of the soil " therefore very unfortunate and misleading, and should it not be entirely given up?

§ 18. *Radium and other Atomic Sources of Energy.*—In the paper on the " Temperature of the Earth " we adhered to the gravitational theory as the only one which could be subjected to strict calculation. It is of course possible that there may exist in our planet unknown sources of atomic or subatomic energy such as are shown in radium and the related elements, which exhibit similar radio-active properties. At present, however, the amount of these elements known to exist in the earth is excessively small, and although this might account for the earth's internal heat; yet as gravitation is known to be a real cause and has been found sufficient to explain the observed phenomena, it is natural that a known source of energy which can be subjected to strict calculation should be preferred to one which is so wholly unknown.

Thus while we confined our estimates and calculations to gravitational energy, we do not deny the possibility that other sources of energy of an atomic or radioactive character may exist. If such sources really exist, the effect would be to prolong the period of the earth's history since consolidation.

At the present it is impossible to estimate these effects with any approach to accuracy, and we have therefore preferred to await the results of future research.

Our knowledge of radium and the rôle it plays in cosmical development is still much too limited to permit even a rough estimate of the effects of such subatomic energy. But it seems certain that radium has no sensible connection with volcanic eruptions, since in the rocks underlying the great extent of the continents it remains quiescent, and gives rise to no kind of outbreaks, though it may raise slightly the temperature of certain mineral springs. Remarkable as radium is, and wonderful as are its chemical actions, we are still unable to say that it plays any sensible part in cosmical processes outside of chemical transformations which lie in the domain of Mineralogy. The energy liberated in these transformations might, however, greatly prolong the past history of the earth, and the total duration might thus be extended from 10 to 100 million years.

III. On the Disturbances of the Earth's Magnetism by Earthquake and Volcanic Phenomena.

§ 19. *Observations Show That Earthquakes and Volcanic Outbreaks Often Disturb Terrestrial Magnetism.*—It has long been noticed that volcanic outbreaks and also earthquakes are not infrequently accompanied by temporary disturbances of the earth's magnetic field. The cause of this is not yet understood and any conjecture at this time may be premature, nevertheless we are inclined to call attention to certain features of these phenomena which should be borne in mind.

1. As the earth's crust is thin, and the interior at an immense temperature, it seems highly probable, if not certain, that the magnetism of the globe depends upon the crust and the atmosphere, together with the sun's variable magnetic field in which our planet

revolves. That the incandescent nucleus could effect the magnetism of the earth seems highly improbable.

2. The annual and diurnal variations of the magnetic needle are most easily explained by the seasonal and diurnal effects of the sun, exerted indirectly through the paramagnetic medium of the atmosphere, the electric forces of which are modified by the sun's varying radiation of charged particles.

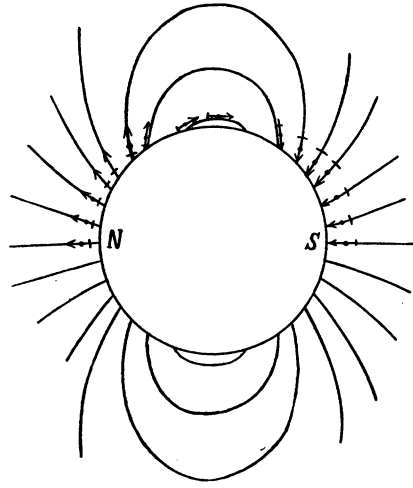


FIG. 4. Showing the lines of force about a spherical magnet, or a magnetized spherical shell, such as the crust of the Earth.

3. The aurora is one of these effects and has been treated by Arrhenius with characteristic penetration.

§ 20. *Gauss' Analysis of the Earth's Magnetism and the Conclusions Which May be Drawn From it.*—If we denote by $d\mu$ the quantity of magnetism present in an element of space, and by ρ its distance from any point in space, whose rectangular coördinates referred to any system may be x, y, z; then we have for the potential function of the earth's magnetism

$$V = \int \frac{d\mu}{\rho}, \qquad (1)$$

where the integration is to be extended over the entire volume of the earth. The forces resolved parallel to the coördinate axes are

$$-\frac{\partial V}{\partial x}=\xi, \quad -\frac{\partial V}{\partial y}=\eta, \quad -\frac{\partial V}{\partial z}=\zeta, \tag{2}$$

and the resulting force is given by the diagonal of the parallelopipedon

$$f=\sqrt{\xi^2+\eta^2+\zeta^2}. \tag{3}$$

If the direction and intensity of the force is found by observation all the desired elements may be calculated.

Passing to polar coördinates Gauss denotes by r the distance of the point from the center of the earth, and by u the angle which r makes with the north polar axis, and by λ the angle with the meridian made by a plane passing through the point and this polar axis. Symbols with subscripts zero refer to points in the earth.

Hence the expression for the distnce ρ from any point in space is

$$\rho^2=r^2-2rr_0[\cos u\cos u_0+\sin u\sin u_0\cos(\lambda-\lambda_0)]+r_0^2. \tag{4}$$

Accordingly the expression for the potential becomes

$$V=\int\frac{d\mu}{\sqrt{r^2-2rr_0[\cos u\cos u_0+\sin u\sin u_0\cos(\lambda-\lambda_0)]+r^2}}. \tag{5}$$

Considering the earth to be a sphere of radius a Gauss puts

$$-V=\frac{a^2}{r}P^0+\frac{a^3}{r^2}P'+\frac{a^4}{r^3}P''+\frac{a^5}{r^4}P'''+\cdots; \tag{6}$$

the coefficients, P^0, P', P'', etc., are functions of λ and u only.

If we develop the denominator under the integral sign in (5) in a series, the first two members of the series become

$$\frac{1}{r}+\frac{r_0}{r^2}[\cos u\cos u_0+\sin u\sin u_0\cos(\lambda-\lambda_0)]+\frac{r_0^2}{r^3}+\cdots, \tag{7}$$

whence

$$a^2P^0=-\int d\mu, \quad a^3P'=-\{\alpha\cos u+\beta\cos\lambda+\gamma\sin u\sin\lambda\},$$

where

$$\alpha=\int r_0d\mu\cos u_0, \quad \beta=\int r_0d\mu\sin u_0\cos\lambda_0, \quad \gamma=\int r_0d\mu\sin u\sin\lambda. \tag{8}$$

As Gauss took the northern and southern magnetism to be equal and of opposite sign, it follows that

$$\int d\mu=0,$$

and $P^0 = 0$. Hence we may put for points at the earth's surface, where $r = a$, and $P^0 = 0$.

$$-V = a(P' + P'' + P''' + \cdots), \tag{9}$$

where P', P'', P''', depend only on u and λ.

The magnetic potential for the earth calculated in this way represents observations with the desired accuracy. Since Gauss showed that any distribution of magnetism within the earth, as respects the effects in outer space, may be completely represented by an appropriate surface distribution, it follows that the existing distribution of the earth's magnetism is most probably confined to the crust of the globe. In fact this is the only part of our planet sufficiently cooled to maintain magnetic properties once established in its elements. The field of force thus arising about the earth might, however, be slightly modified by electric and other effects depending on the sun and moon, and the diurnal movement of the illuminated hemispheres of our globe. These effects as determined by observation are much too large to be ascribed to direct actions of the sun and moon, and are believed to be indirect effects depending largely on charges operating in the upper regions of our atmosphere.

This upper atmosphere is always exposed to the radiation of the heavenly bodies, and no doubt accumulates a potential powerful enough to influence the field near the earth's surface. Discharge of this potential is witnessed in the aurora borealis, which is accompanied by conspicuous disturbances of the earth's magnetism. Gauss showed that the location of the constant part of the earth's magnetism must necessarily be in the body of the globe, and not in the atmosphere or outer space.

In his "Algemeine Theorie des Erdmagnetismus," 1838, Gauss treated of a sphere magnetised in any manner. If X, Y, Z, be the components of the earth's resultant magnetic force at any point on the surface, in the directions of geographical north, west and the zenith of observer, the horizontal intensity H, declination δ, and inclination ι, are fully defined by the equations:

$$H = \sqrt{X^2 + Y^2}, \quad \tan \delta = \frac{Y}{X}, \quad \tan \iota = \frac{Z}{\sqrt{X^2 + Y^2}}. \tag{10}$$

If V be the magnetic potential of the earth, l the latitude, and λ the longitude of any point on its surface, and if a be the radius of the earth assumed to be spherical, we shall have

$$X = -\frac{1}{a}\frac{\partial V}{\partial l}, \quad Y = -\frac{1}{a\cos l}\frac{\partial V}{\partial \lambda}, \quad Z = -\frac{\partial V}{\partial r}, \qquad (11)$$

where r is the distance of any point from the center of the earth.

If $S_1 + S_2 + S_3 + \cdots S_i$ be a convergent series of spherical surface harmonics defining for every point of its surface the potential of all the magnetized molten or electric currents within the earth, the potential at all external points will be given by the series

$$V = S_1\left(\frac{a}{r}\right)^2 + S_2\left(\frac{a}{r}\right)^3 + \cdots + S_i\left(\frac{a}{r}\right)^{i+1}, \qquad (12)$$

The functions S_1, S_2, S_3, . . . are functions of known form, containing 3, 5, $\cdots 2i + 1$ constants; and if we neglect terms beyond the ith order, there will remain in the expression for V $i^2 + 2i$ arbitrary constants. These constants may be determined by observation, and then the magnetic action at all points on the surface or outside the earth becomes known irrespective of the internal distribution of the magnetic causes which are inaccessible to observation.

§ 21. *The Mutual Potential Energy and Mutual Action of Two Magnetic Systems.*—If any portion of the earth's crust or an atmospheric current above it should be suddenly magnetized by an instantaneous charge of electricity or otherwise, during the violent commotion of an earthquake or volcanic outburst, we should have at least a temporary magnet suddenly formed in the field of the earth's magnetism, and the result would be the disturbance of the magnetic needle. Whether the magnetism of the earth be distributed according to Poisson's theory, with a certain volume distribution of density v and a surface distribution of density σ; or according to Gauss' theory, with a distribution wholly on the surface, this result is equally true.

To determine the mutual action of two magnets on each other requires the evaluation of a sextuple integral, every point in one field of space acting upon the corresponding points of the other. If W be the potential energy of the whole magnetic system, R and R'

the resultant forces at any point of space due to the acting and acted-upon systems respectively, θ the angle between their directions, and dv the element of volume occupied by any element of magnetism, we have (Encyclopedia Britannica, article "Magnetism," p. 230):

$$W = +\frac{1}{4\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} RR' \cos\theta dv. \qquad (13)$$

Now unless R or R' is zero, so that the elements of the triple integral vanish, or one of the magnets exerts only an infinitesimal force upon the other, this mutual potential energy is always finite. Accordingly, whenever a new magnet of sensible power is suddenly developed in the field of the earth's magnetism, the magnetic needle necessarily is disturbed, as in earthquakes and volcanic outbursts. The fact that such disturbances are so repeatedly observed, leaves no doubt of the development of temporary magnets in the earth's field of force; and the intensity of the disturbance necessarily is greatest near the place where the second magnet is developed. Hence the disturbance of the needle by such outbreaks indicates the generation of temporary magnets in the earth's crust, and especially in the atmosphere. The dissipation of the charge restores quiescence to the earth's magnetic field, and the needle ceases to tremble.

§ 22. *Terrestrial Magnetism Modified by Irregularities in the Earth's Crust.*—In the *National Geographic Magazine* for September, 1907, Dr. L. A. Bauer has a review of the work done by the *Galilee* in the survey of the North Pacific ocean authorized by the Carnegie Institution. After describing the work already done he adds:

> "An all-sailing vessel, however, does not permit the magnetic survey to be undertaken with the completeness and success demanded, since with such a vessel it is more or less dangerous to investigate the magnetic irregularities almost invariably shown to exist near land masses. The mapping of these irregularities is of the greatest importance to the mariner, as in many cases they are sufficient, if not allowed for, to land a vessel on the rocks."

The land masses accessible to the navigator are either islands or shores, and thus irregularities of surface like the mountains which we see on land; and the change in the magnetism near mountains is also well known. It follows therefore that irregularities of sur-

face sensibly affect the magnetic needle in the neighboring region. This conspicuous effect would not be likely to arise if the magnetism depended on the whole earth, rather than on the crust, and hence it seems to indicate that the seat of the earth's magnetism is essentially shallow. Not only may we attribute the permanent magnetism to the crust, but we may also affirm that the upheavals of the crust which have produced mountains have given rise to variations of the local field.

Just how this arises may not be affirmed with entire certainty; but the fact that disturbances have been noted during earthquakes would seem to indicate bodily movement of magnetic matter, or ordinary matter temporarily rendered magnetic.

The outburst at Mt. Pelée, May 8, 1902, which instantly disturbed the magnetic needle over a wide area, was probably due to the ejection of a great mass of burning vapor high into the air, which thus gave rise to such electric energy that the earth's magnetic field was suddenly disturbed.

The eruption at Krakatoa produced a very similar effect, the sudden development of an atmospheric charge vastly exceeding that due to the greatest hurricane. (Report of the Krakatoa Committee, Royal Society, 1887.) A hurricane develops gradually and the effect is scattered over a wide area; a volcanic outburst is sudden and so concentrated that a considerable disturbance of the earth's magnetic field may easily result. It is somewhat analogous to the aurora borealis, but the location and cause is different and the effect may be less rapid. In the aurora there is a discharge between the upper and lower regions of the atmosphere, and this redistribution of the magnetic tension in the earth's atmospheric system causes a fluctuation of the magnetic needle, or a so-called magnetic storm.

Now in the case of a violent volcanic outbreak there is a similar disturbance, owing to the sudden injection of a highly electrified charge into the lower parts of the atmosphere, and the exchange with the upper region continues for some time. Also when great earthquakes occur there is violent shaking of a considerable region of the earth's crust, and consequently some temporary, and perhaps permanent, derangement of the elements of magnetism, owing

to the agitation and to the movement of streams beneath the crust. These seem to be the most probable causes of the changes in the earth's magnetic field, often noticed to disturb the needle at the time of earthquakes and volcanic eruptions; but our knowledge of the subject is still in its infancy and we must be cautious in drawing conclusions. Some of the disturbances of course are purely mechanical.

The comparatively slow propagation (868 miles per hour) of the magnetic disturbance at the time of the Krakatoa outbreak, August 27, 1883, might be ascribed to the undulatory commotion in the upper air, since sound so propagated would have about this velocity. It would seem to depend more upon the indirect effects of a disturbance of the air than upon the forces exerted by a direct magnetic charge. Both causes are no doubt at work in certain disturbances, and time must decide just how the effects are propagated.

Conclusion.

At the close of the two former papers on the physics of the earth, the chief results at which we arrived are briefly summarized. In the same way we may here add a recapitulation of the results which are more fully established in this third paper.

1. It has long been customary to refer mountain making to catastrophes in remote geological ages, and to suppose that the formation of mountains is not going on upon the earth at the present time. Such supposed spasmodic activity is contrary to the whole order of nature and to the doctrine of evolution by which we labor to interpret animate and inanimate phenomena. On the other hand the discovery of mountains in the depths of the sea has excited the surprise without satisfying the wonder of the naturalist, so that the whole subject has become involved in darkness.

2. The doctrine of continuity, as respects both time and space, permits us to view earthquakes, mountain formation, and kindred phenomena, merely as a part of an unbroken whole which has come about by the steady action of natural laws operating not only along the borders of the continents, but also in the depths of the ocean. A theory which unites and harmonizes these phenomena,

and thus explains the mountains on land, as well as those in the depths of the sea, by a common cause, operating not only throughout past geological ages, but also at the present time, will naturally have a strong claim to acceptance.

3. We have therefore labored to establish some undeniable cases of mountain formation now going on in the depths of the sea, and have shown by the theory of probability, based merely on contiguity of positions and similarity of volume between the deep trench off the Aleutian Islands and the ridge which runs parallel to it, with peaks here and there projecting above the water as islands, that the chances are at least a decillion decillions to one that the ridge and adjacent depression are physically connected and have had a common origin. As an island of the ridge is frequently uplifted by an earthquake, while the bottom of the trench sinks, as shown by the withdrawal of the water before the inrush of the accompanying seismic sea wave; and as this corresponds to an expulsion of lava from beneath the trench towards the land, or away from the body of the Pacific ocean, and the volume of the ridge corresponds to that of the trench, the probability that one developed from the other is converted into an absolute certainty.

4. The expulsion of lava from the ocean towards the land and the breaking out of numerous islands into volcanoes, emitting chiefly vapor of steam, shows that the subterranean movement can depend on nothing whatever but the secular leakage of the ocean bottom, which is most rapid where the sea is deepest, in accordance with the observed recurrence of earthquake phenomena.

5. Undeniable cases of mountain formation now going on in the depths of the sea may thus be located in various parts of the world. We have cited such cases in the Aleutian, Kurile, and Japanese islands; in the East Indies, between New Zealand and Samoa, and along the coasts of various continents. Many more may be found by the further study of the sea bottom and of the earthquakes now disturbing it.

6. It thus seems undeniable that earthquakes in the sea and along the sea coasts have the highest geological significance. In fact no other forces are at work crumpling the earth's crust, as seen in mountain ranges, islands, and plateaus; and the absence

of mountain forming movements in the interior of the continents shows that all these effects depend upon the sea, or upon surface water generally, and not at all upon the progress of the secular cooling of the globe.

7. Researches into the physics of the earth based on the hypothesis of gravitational instability may be interesting mathematically, but a study of the earth's surface shows that all the important crustal movements now going on result from the influence of the sea; and hence the conclusions deduced from the theory of gravitational instability are invalid, because, ingenious and correct as they are on the hypothesis, they rest on a false premise.

8. In the same way it is shown that no sensible shrinkage results from secular cooling; on the contrary the globe seems to be undergoing a gradual secular expansion, owing to the influence of the sea in uplifting mountains, plateaus and other masses of land, by the injection of lava saturated with steam, which forms underlying masses of pumice of various degrees of density. The expansion of the globe seems to be at least ten times more rapid than the contraction due to secular cooling; and the great distance to which the sea has withdrawn from some of the mountain ranges, and the great height to which the plateaus have been uplifted, exhibits the mighty effects of this cause in the course of geological ages.

9. The seat of terrestrial magnetism seems to be the earth's crust and the surrounding atmosphere; irregularities in the magnetic forces arise from the sun and moon, while similar disturbances accompany earthquakes and volcanic outbreaks, which suddenly agitate the air and change the electric condition of matter in the field of the earth's magnetism. The irregularities near islands and land masses noticed in ocean surveys indicate that the permanent magnetism is confined chiefly to the solid crust, and does not depend on the great incandescent nucleus of the globe. Magnetic storms and aurorae depend on atmospheric charges derived principally from the sun and moon.

10. It is thus proved not only that earthquakes, volcanoes, mountain formation, the formation of islands and plateaus, seismic sea waves, and the feeble attraction of mountains long noticed in

geodesy, are closely connected and mutually dependent upon a single physical cause, namely the secular leakage of the ocean bottoms; but also that the magnetism of the earth is intimately connected with the forces which modify the earth's crust, because the chief seat of the permanent magnetism is shallow. Thus seven great classes of natural phenomena are shown to be mutually connected and dependent on the forces which have crumpled the crust of our planet.

11. In the paper on the temperature of the earth it was shown from the mathematical theory of heat as applied to the secular cooling of the globe that when the gravitational potential of the mass alone is the source of energy considered, the most probable age of the consolidated earth is some ten million years. Variations of the data there used might possibly double this age, but it is doubtful if further extension of the time limit of the past history of our planet is possible without invoking the aid of subatomic energies as exemplified in radium and kindred radio-active substances. At present we know too little of radium and similar elements to be able to affirm with confidence that the heat resulting from the transformation of these substances does not prolong the life of our planet; yet as radium has no known connection with volcanoes, earthquakes, and mountain formation, but, from the absence of outbreaks in the interior of continents, seems to be everywhere in an essentially quiescent or dormant condition, it is natural to infer that it plays only a subordinate part in cosmical processes. It may, however, be of great importance in chemical transformations, which belong to the domain of Mineralogy, and relate to the crust, rather than to the body, of our globe. Without, therefore, wholly denying the cosmical importance of radium, we calmly await developments which will show its correct place in the order of nature. As the energy derived from radium would counteract the effects of secular cooling it may have greatly prolonged the history of the encrusted earth.

12. In the investigation of phenomena so complex as those connected with the physics of the earth, we must not expect the real underlying physical cause to be entirely clear in every case, because the present state of the globe presents to our contemplation natural

processes in every stage of development, and the aspect obviously will be different in different stages. If we can find the true laws exemplified in a few typical cases in which the meaning of the phenomena is free from doubt, we may legimately hold that in all cases the phenomena were more or less similar at one stage of their existence. Considering the vast age of the earth and the insignificant period of human history, and the much briefer time covered by intelligent observations, we seem indeed fortunate to be able to recognize the true processes in even a few typical cases of crustal transformation. For the life of the individual is as nothing in the history of our planet. Accordingly the simplest natural laws, which lie at the basis of the physics of the earth, we have discovered and confirmed beyond all doubt; and we may safely leave to the future the extension and verification of the theory of the secular leakage of the ocean bottoms, of which we have been able to lay only the general foundation.

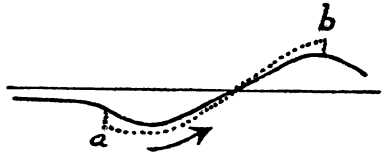
But even a mere outline of the processes which lie at the basis of the physics of the earth is likely to clarify and simplify our views of the order of nature. The complete development of that beautiful science will be a work of the future, and for the present we must rest content with the recognition of true physical causes, without which order and harmony and proper relationship between different classes of phenomena could not be established, however great the number of observations. The chief danger in science to-day is that in the midst of such vast multitudes of special observations as are being accumulated, the few true causes, which give order and harmony to the whole body of phenomena, will be lost sight of. Without these underlying principles for guiding our thought, according to nature's laws, the mere accumulation of disconnected facts may become a burden to oppress, rather than a starry ray to illuminate, the human mind. Principles are therefore vastly more important than observations, though accurate observations always are required in their deduction; because where the underlying laws are confirmed they give the solid foundations for a real science, which enable us to understand the observations of all time.

BLUE RIDGE ON LOUTRE,
MONTGOMERY CITY, MISSOURI, October 24, 1907.

ADDENDUM.

§ 23. *On the Sinking of Deep Trenches in the Sea Bottom.*—Since the above paper was finished it has occurred to the writer to point out a little more clearly the circumstances which may lead to the sinking of the sea bottom, when lava is expelled from beneath it. In the accompanying figure, the process of mountain formation is supposed to be going on. The expulsions of lava naturally are accompanied by a sudden relief of crustal stress, and a mighty horizontal thrust in the direction of the movement, as the lava is pushed under the land.

This terrific lateral pressure is powerful enough to push the lava along under the crust, in spite of the great weight of the latter. By this enforced movement the ridge is elevated, as at *b,* and at the



same time the crustal block moved a good many feet in the direction of the land; this stretches the sagging crust, and pulls it apart along certain fault lines under the sea, as at *a;* so that when some of the support from beneath is withdrawn by the expulsion of part of the supporting lava, and the fault opened, by the horizontal movement, the crust naturally gives down. The shaking accompanying the horizontal thrust of the crust opens the fault under the sea, thus temporarily removing the friction of one crustal block against another and permitting the walls to slide without great resistance. And as the support is weakened by the simultaneous expulsion of part of the underlying lava, sinking necessarily follows.

From these considerations we see that sinking is most easily brought about where the ridge is sharply elevated so as to permit some lateral movement. It is true that the inclination of the crustal block throws a little more weight on the side under the sea and this would increase the resistance; yet when the fault is opened during the vibrations of an earthquake sinking the more easily takes place. This explanation enables us to understand why sinking of the sea

bottom, as shown by the accompanying seismic sea wave, so frequently occurs during great earthquakes.

The force of the argument that the ridge was uplifted by matter actually expelled from under the trench is easily seen from a familiar illustration often met with in a smooth field or on the plains. If we go along over the level ground, and all of a sudden come upon a mound with a sink hole near it of about the same volume, we immediately conclude that the mound builders or pond diggers have been at work. It is obvious that the mound is made of soil which came out of the hole. In the same way, if we came upon a ditch with a ridge to one side, of such volume that it would about fill up the former, we know with even greater certainty that ditch diggers have taken the soil out of the trench and piled it upon the bank.

Now the trenches in the sea bottom, with parallel ridges of nearly equal volume, have all the force of this familiar argument; but as they have not been dug from above, it follows that the matter is transferred beneath the crust, by subterranean bodily movement of the kind we have described; and hence the crust has been crumpled correspondingly, the ridge running parallel to the trench from which the matter was expelled.

§ 24. *On Darwin's Theory of Coral Islands.*—This investigation throws decided light upon Charles Darwin's famous theory of the sinking of the ocean bottom, as inferred from the study of the coral reefs. It shows that while sinking often takes place, elevation also is very common. The chief difference is that elevation kills the coral, and the islands gradually become covered with vegetation, while only those in which sinking predominates become surrounded by coral reefs. It is well known that there are many islands in the sea with coral rock above the water; a good illustration is afforded by the eastern end of Guam, where a huge block has been uplifted, as shown by the vertical walls. Islands which have been recently uplifted often are volcanic, so that coral appears especially about old islands, many of which are subsiding, owing to a change in the direction of movement beneath the crust. Forces which formerly produced elevation are now changed in direction and working so as to produce a slow subsidence. Charles Darwin's theory of coral reefs is therefore confirmed, but it does not explain all the phe-

nomena noticed about the islands in the sea. It happens also that some islands once built around by coral are again upraised by a recurrence of the elevating movement; yet this probably would not be the usual phenomenon, so that in general Darwin's observations on coral reefs accord with the theory, and are what one might naturally expect to find on an ocean-covered planet with leaky and oscillating crust.

§ 25. *On the Modification of Secular Cooling by Radium.*—In regard to the age of the earth, it ought to be remarked that if radium be taken into account, the heat resulting from its secular disintegration would prevent the crust from thickening, except very slowly; and consequently with so thin a crust as that of our actual globe the period of time since the consolidation, as calculated in the paper on the "Temperature of the Earth," is too small. Accordingly although we found the period to be of the order of ten million years, yet if radium be introduced the duration of time might be lengthened to one hundred million years, or even to a greater period. And if this energy due to radium be admitted for the earth, it could not well be denied for the sun, so that the period of the sun's activity would be lengthened correspondingly. Hence the more moderate of the immense periods of time demanded by geological phenomena may be conceded. Time must decide to what extent these demands are justifiable. At present we may await future developments with entire confidence that the causes now known are sufficient to explain all terrestrial phenomena.

§ 26. *Favorable Reception of the Present Theory by Physicists and Geologists.*—The lively interest awakened by the two preceding papers among physicists and geologists and other men of science, as shown by letters which have reached the writer, indicates a much more favorable reception of the present theory than might have been anticipated. Indeed its general acceptance seems fully assured, and many questions are thus raised of great importance in natural philosophy. All who have considered the question attentively seem to agree that it is very improbable that the ocean bottom is watertight. One of the most eminent of living physicists expresses the opinion that this cannot be true, unless the nature of the rock is greatly modified by pressure. Such modification under pressure he

thinks cannot take place in the first twenty miles of the earth's crust, because the pressure is not great enough to prevent secular leakage under the constant pressure of the oceans, which in many places is sufficiently powerful to throw a column of water five miles high.

No doubt this view will be generally adopted by physicists and geologists. One may indeed see that it is true by remembering that at a depth of twenty miles the pressure is only about 8,600 atmospheres, or a little over eight times what it is in the deepest oceans. Such pressure might indeed tighten the crystalline elements of granite, but it could not obliterate the crystals; and hence capillary forces would be intensified rather than diminished by this tightening up of such a coarse-grained structure.

We cannot experiment on rock subjected to such pressure as exists at a depth of twenty miles, but we can observe lava expelled from volcanoes, some of which was once compressed at this depth; and we can examine the granite at the base of vertical walls where faults have moved under earthquake forces for many thousands of feet. In neither case does the structure of the rock indicate that great modification would occur at so small a depth as twenty miles.

But the most conclusive answer which nature gives to this inquiry is furnished by the vast vertical walls of granite so often lifted thousands of feet by fault movements in such places as the Andes of Peru, Chile and Patagonia, where the leakage of the ocean has found relief by the expulsion of lava under the land along the margins of the sea. The meaning of the mountain formation along such a sea coast admits of no possible doubt. Accordingly we are enabled to interpret the movements beneath the crust, and to infer the nature of the underlying rock, even where it is wholly inaccessible to observation.

BLUE RIDGE ON LOUTRE,
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